# Neutrinos in Large-scale structure

Marilena LoVerde
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ML and Zaldarriaga 1310.6459
ML 1405.4855
ML 1404:4858
ML in prep.

# Outline

- Neutrinos
- Neutrinos in Cosmology
- Massive Neutrinos in Large-scale structure
  - Halo bias
  - Halo abundance
  - Neutrino halos
- Observational Consequences

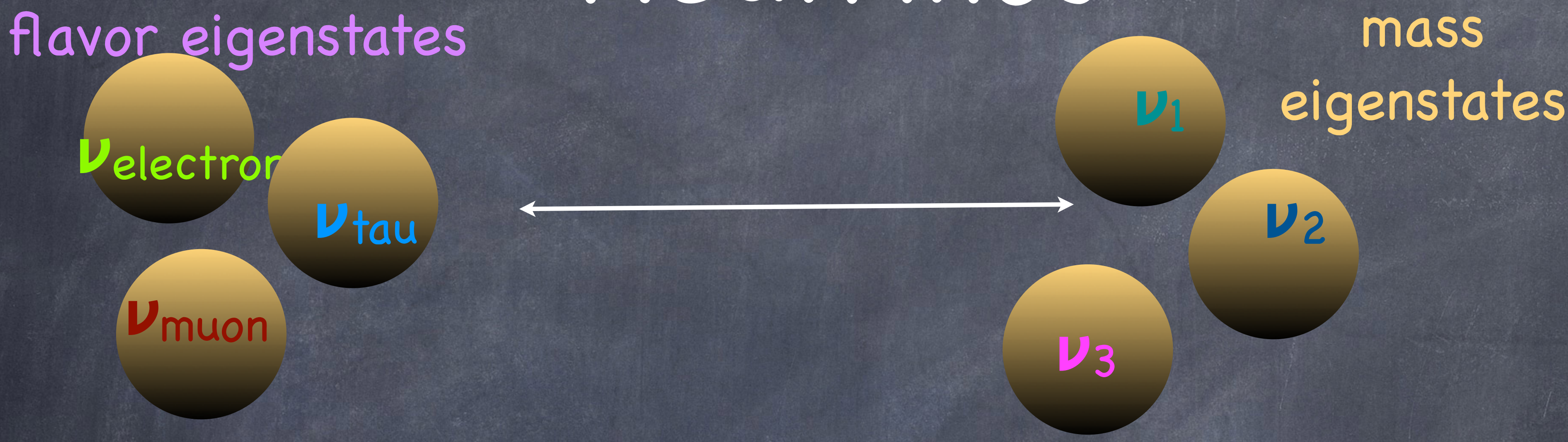
# Neutrinos

# Neutrinos

flavor eigenstates


Pontecorvo 1957, 1958, 1967; Maki, Nakagawa, Sakata 1962

# Neutrinos

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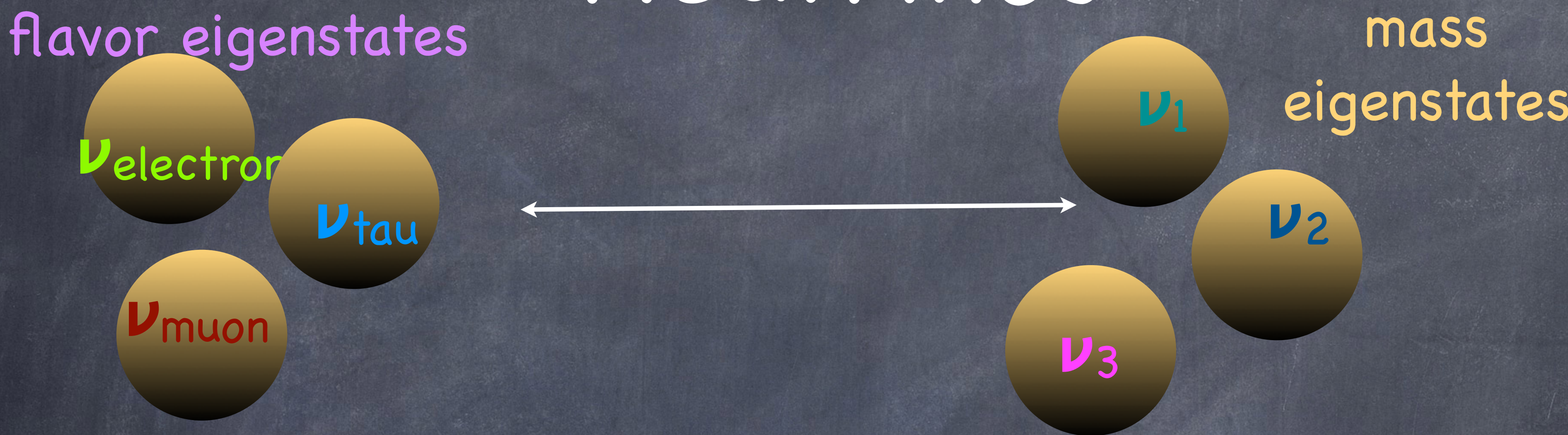
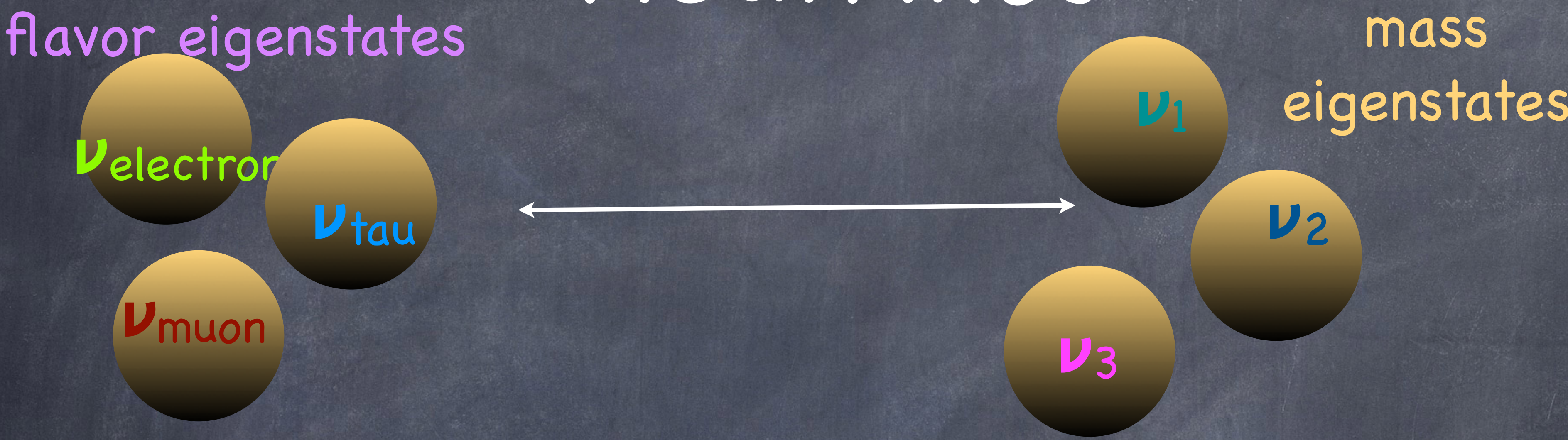



flavor eigenstates ≠ mass eigenstates

Pontecorvo 1957, 1958, 1967; Maki, Nakagawa, Sakata 1962

# Neutrinos




## oscillation data gives mass splittings

$m_2^2 - m_1^2 = (7.5 \pm 0.2)\ 10^{-5}\ \mathrm{eV}^2$ (solar neutrino oscillations)

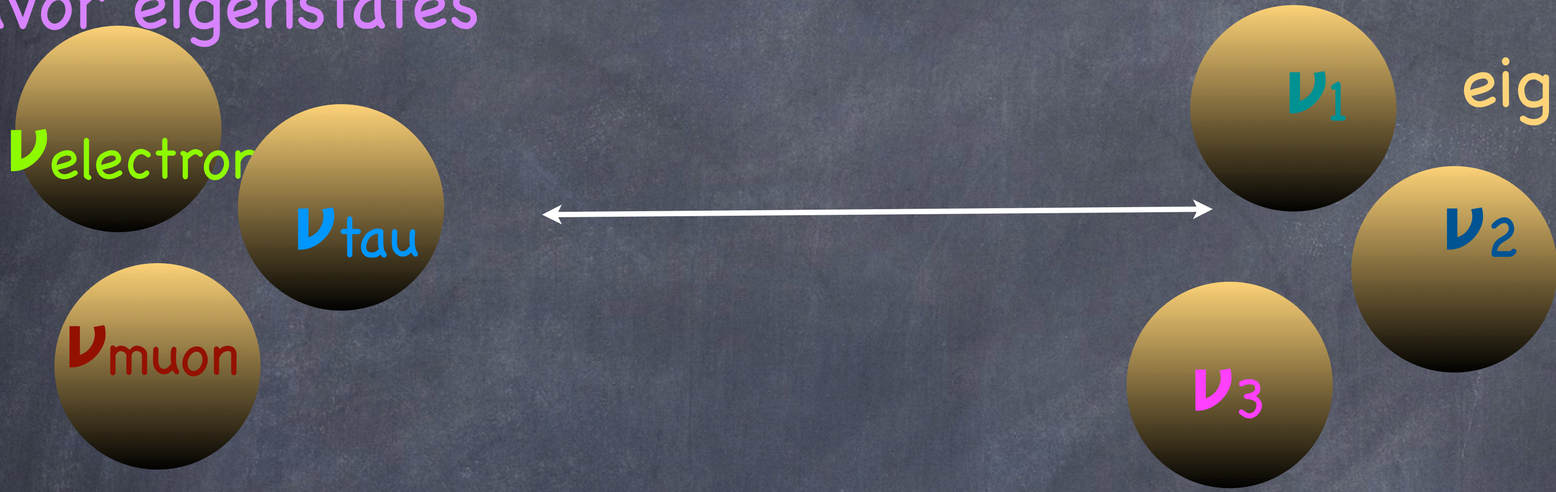
$|m_3^2 - m_2^2| = (2.32^{+0.12}_{-0.08})\ 10^{-3}\ \mathrm{eV}^2$ (atmospheric neutrino oscillations)

Pontecorvo 1957, 1958, 1967; Maki, Nakagawa, Sakata 1962

# Neutrinos

flavor eigenstates

mass eigenstates




but the absolute masses are unknown!

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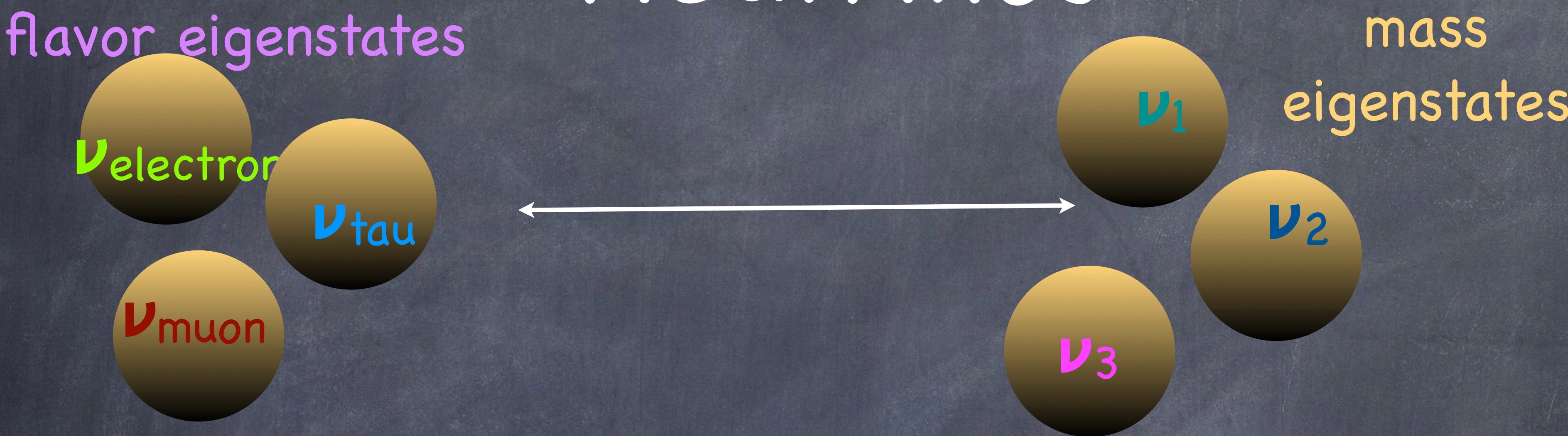


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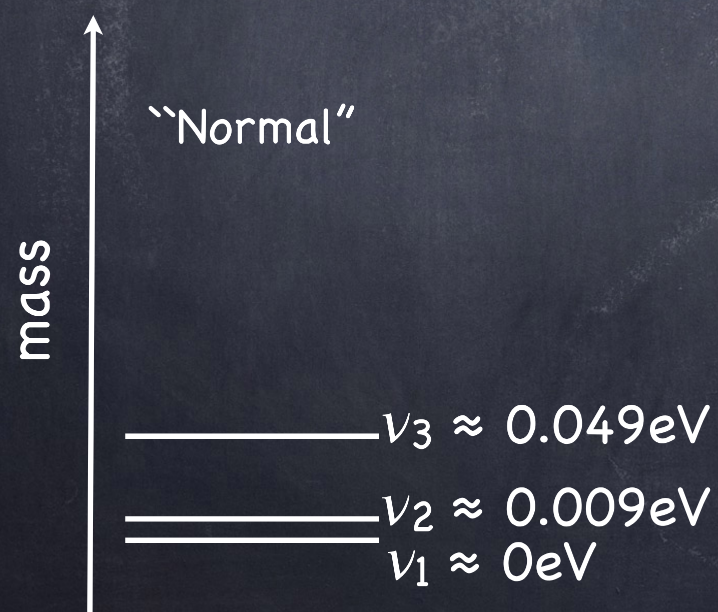


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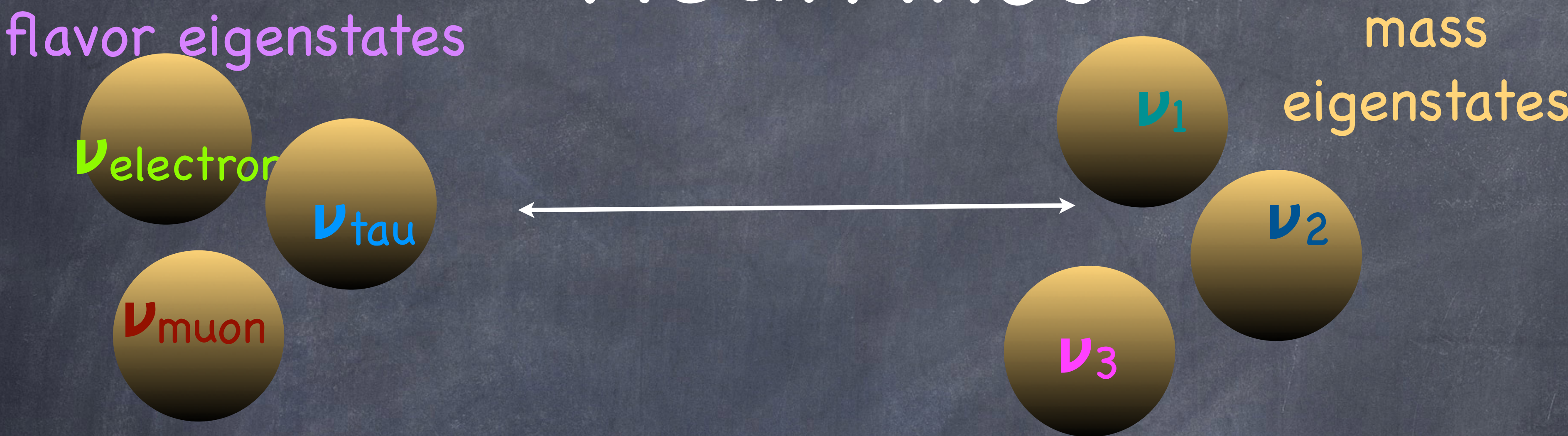


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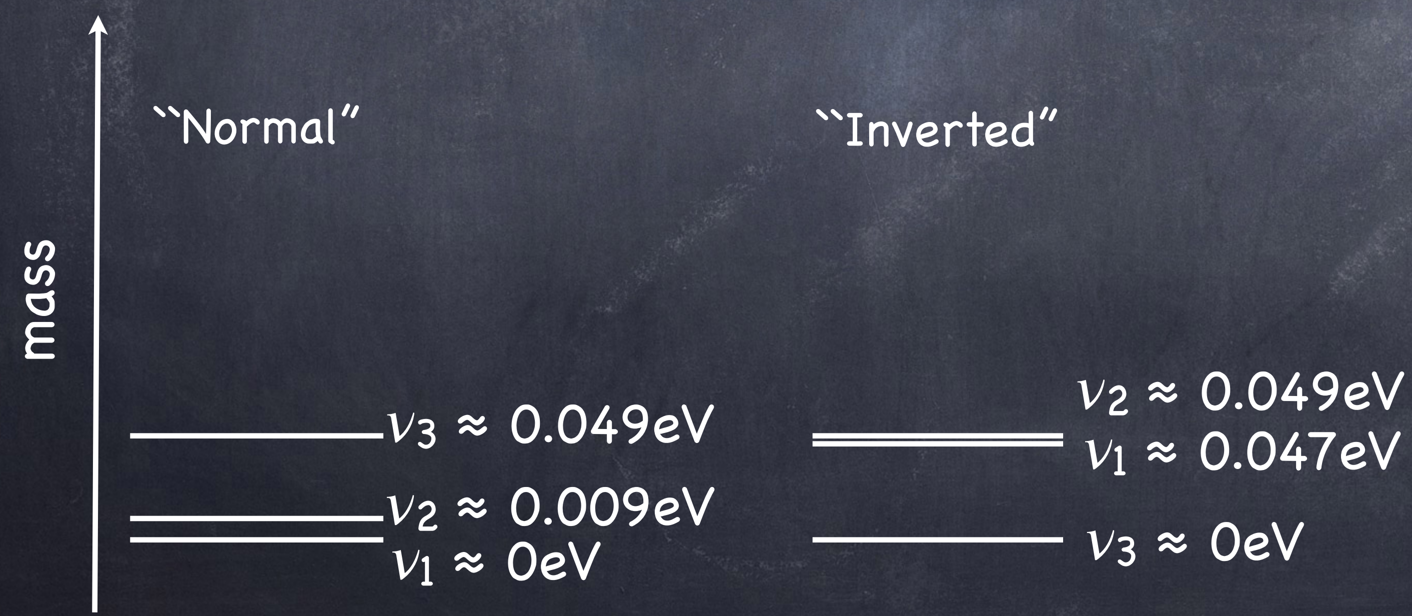


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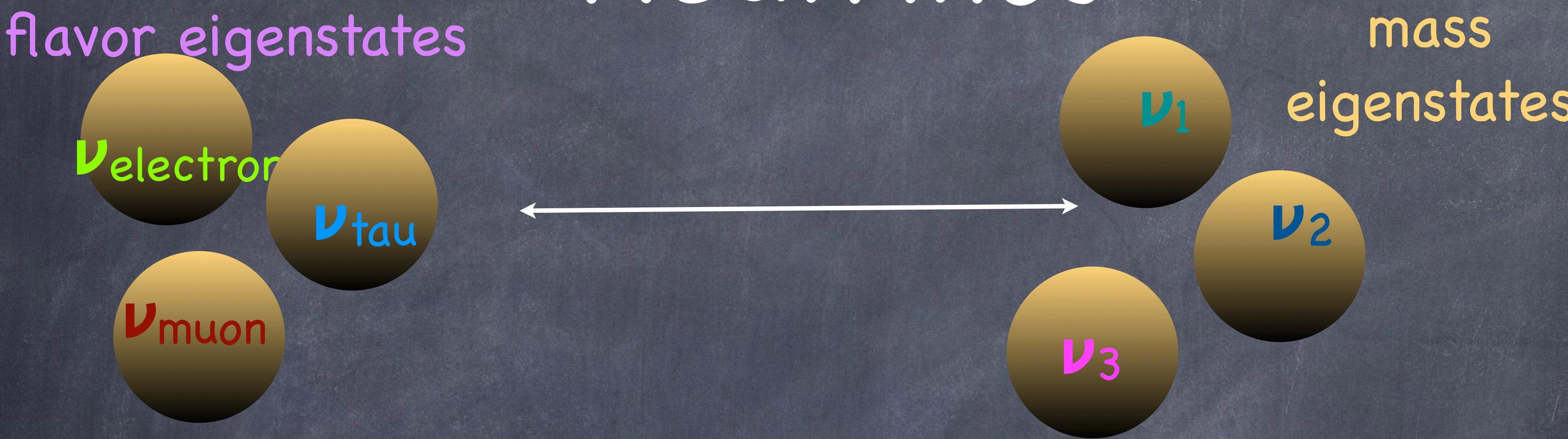


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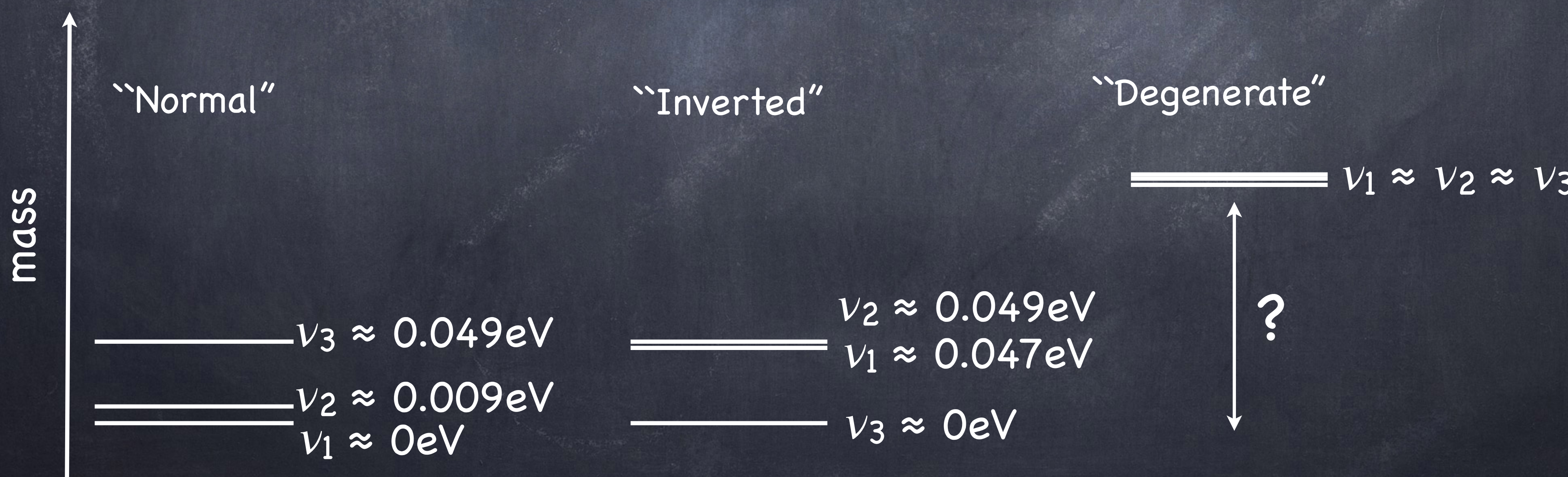


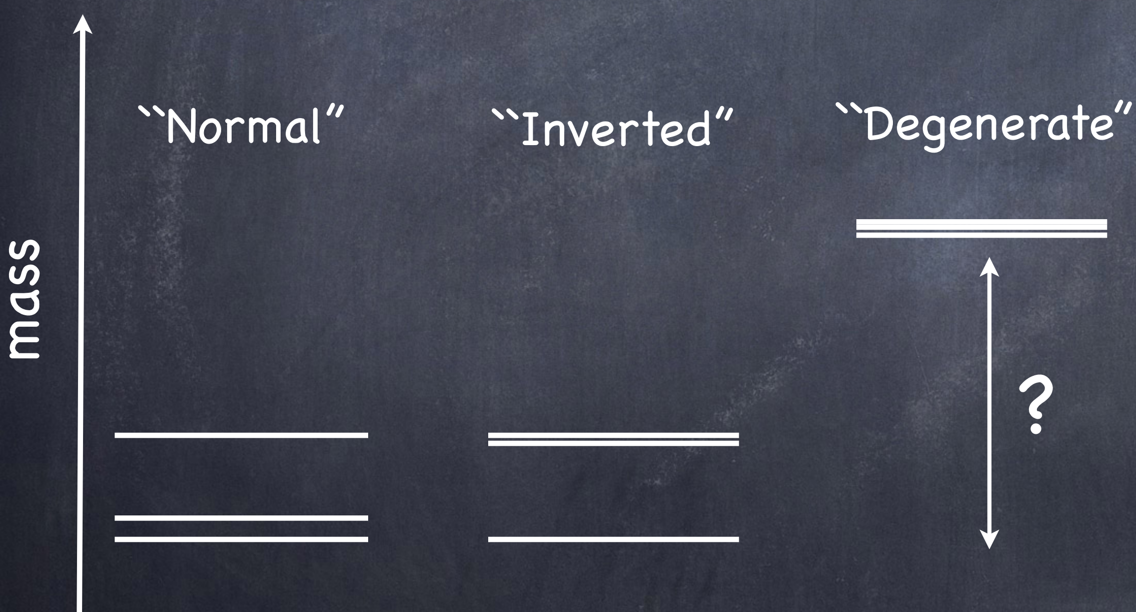

Pontecorvo 1957, 1958, 1967; Maki, Nakagawa, Sakata 1962

# Neutrino knowns and unknowns

## Absolute scale, hierarchy

Tritium $\beta$ decay: $m_{\nu_{\bar{e}}} \lesssim$ 2eV
upper bound on mass
(Troitsk experiment 2011)

cosmology: $\Sigma\, m_{\nu_i} \lesssim$ 0.2-0.6eV
upper bound on mass
(Planck CMB + BAO 2013)




$\nu_i \gtrsim$ 0.05eV
lower bound on mass
from oscillation data

# Neutrino knowns and unknowns

Big Questions

- Where do neutrino masses come from?
- What is the absolute mass scale?
- Are there additional sterile neutrinos?
- Can neutrinos generate matter-antimatter asymmetry of the universe?

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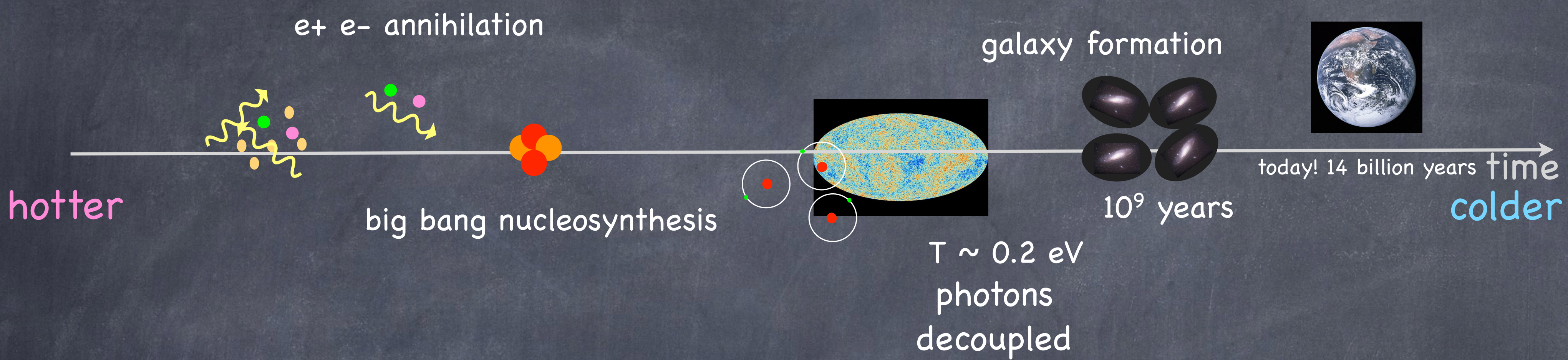
Astrophysics has previously informed neutrino physics!
(solar neutrino problem $\Longrightarrow$ neutrino oscillations)

# Neutrinos in Cosmology

# Neutrinos in the Standard Cosmology



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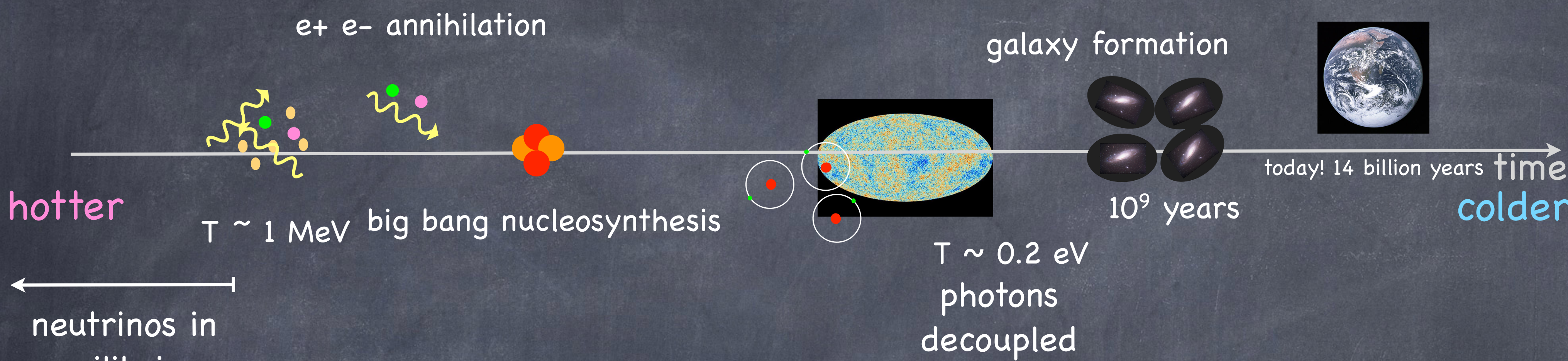
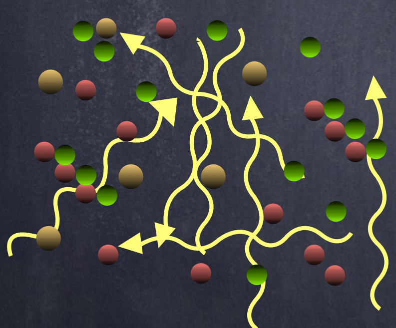



neutrinos in equilibrium with photons e+, e-

$T_\gamma = T_\nu \propto 1/a$



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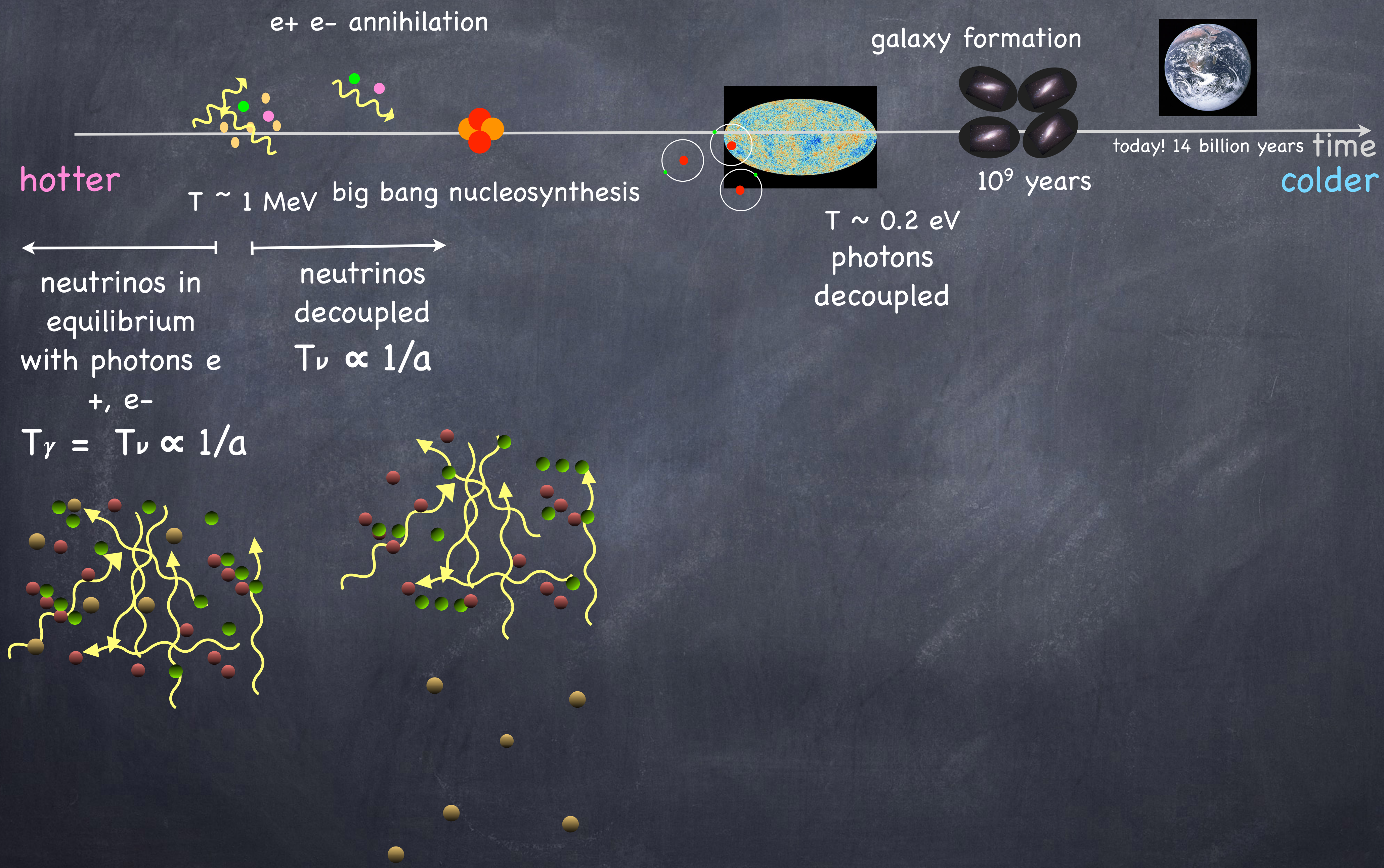

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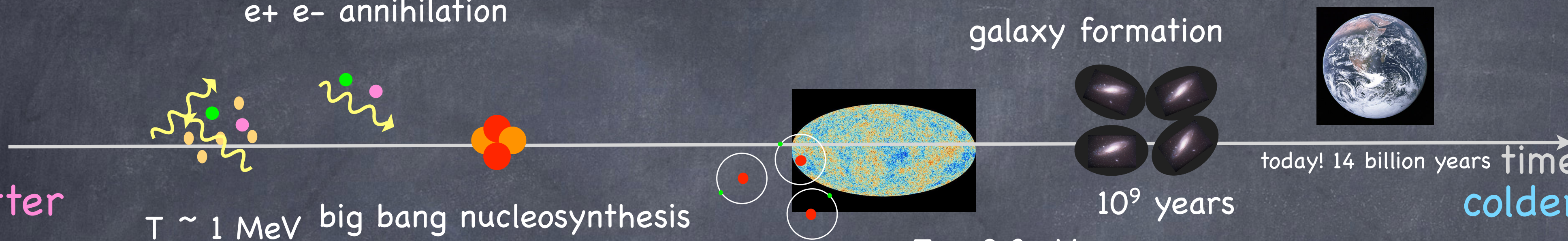



neutrinos in equilibrium with photons e +, e-

$T_\gamma = T_\nu \propto 1/a$

neutrinos decoupled

$T_\nu \propto 1/a$

decouple while relativistic

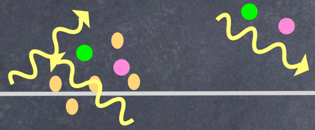
$$n_{1\nu} \sim T_\nu^3$$

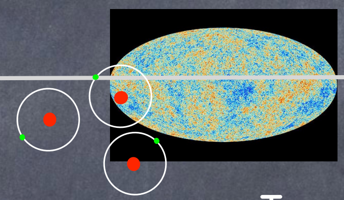
$$\rho_{1\nu} \sim T_\nu^4$$

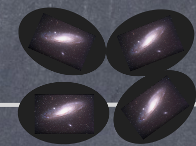
# Neutrinos in the Standard Cosmology

e+ e− annihilation, $T_\gamma$ boosted
relative to $T_\nu$ , $T_\gamma \propto 1/a$

galaxy formation







today! 14 billion years time

hotter

colder

T ~ 1 MeV big bang nucleosynthesis

$10^9$ years

T ~ 0.2 eV
photons
decoupled

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$n_{1\nu} \sim T_\nu^3$

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$$T_\gamma \approx \left(\frac{11}{4}\right)^{1/3} T_\nu$$

$n_{1\nu} \approx 100/\mathrm{cm}^3$

$T_\nu \approx 0.17$ meV

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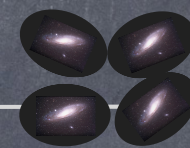

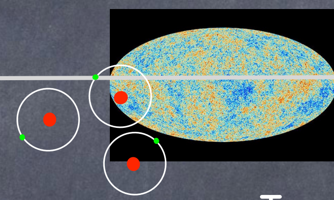

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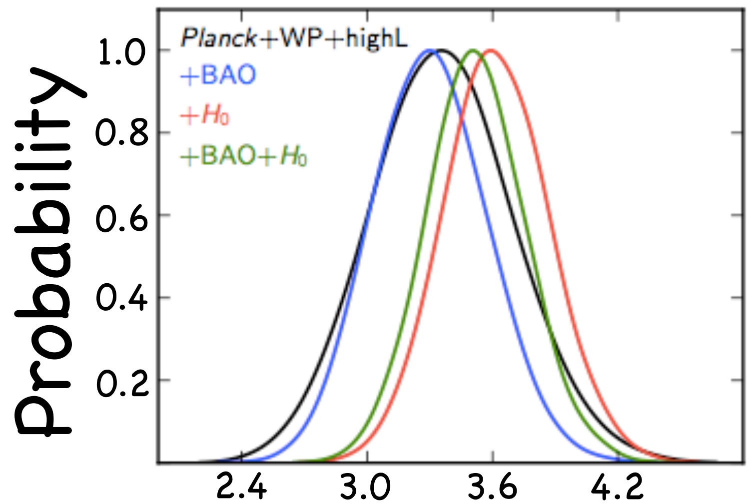
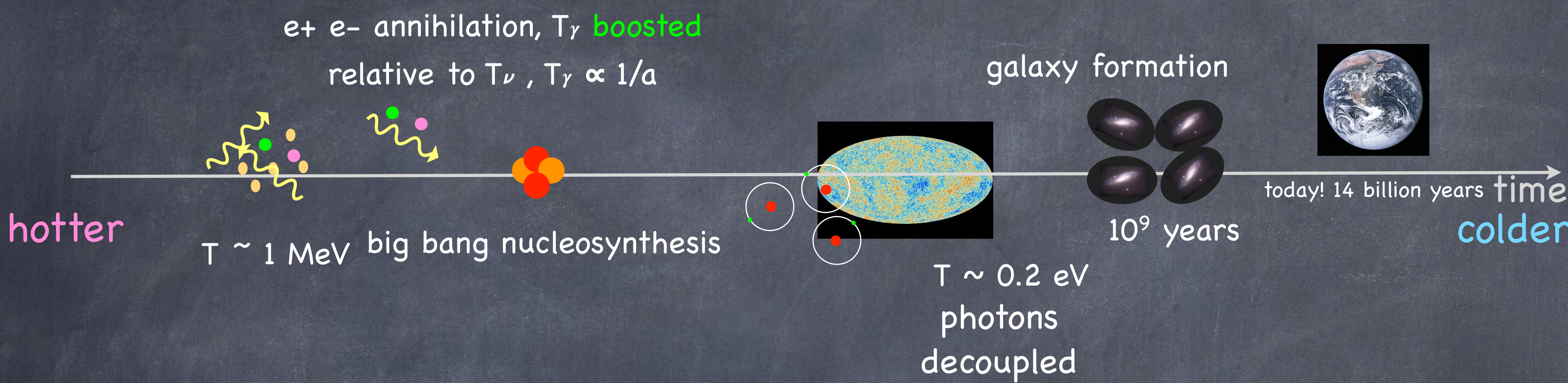
Planck Data




number of fermions with
$T_f \approx (4/11)^{1/3}\, T_\gamma$

Ade et al 2013

# Neutrinos in the Standard Cosmology




Once $T_\nu \ll m_\nu$ energy density is just

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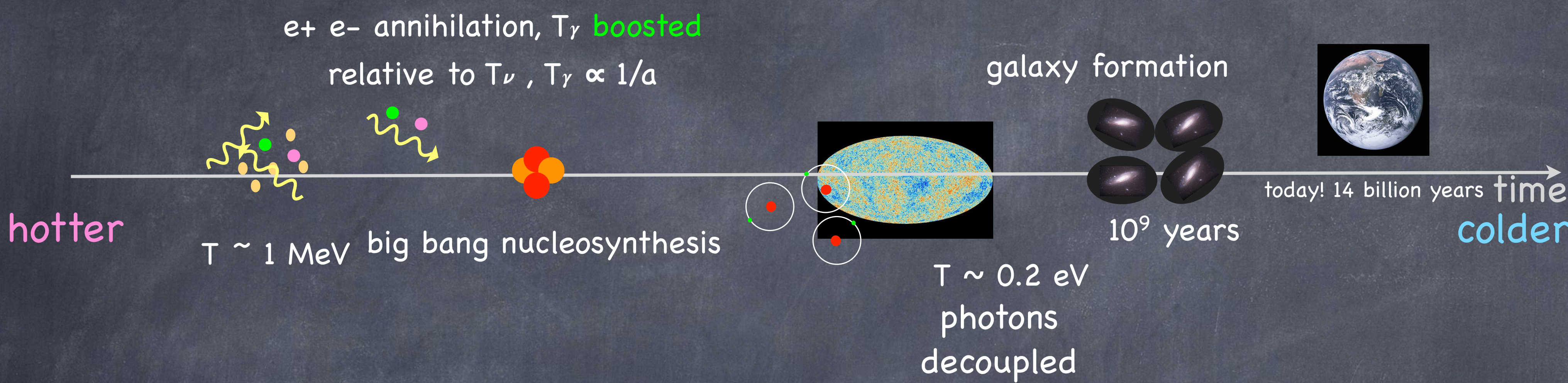


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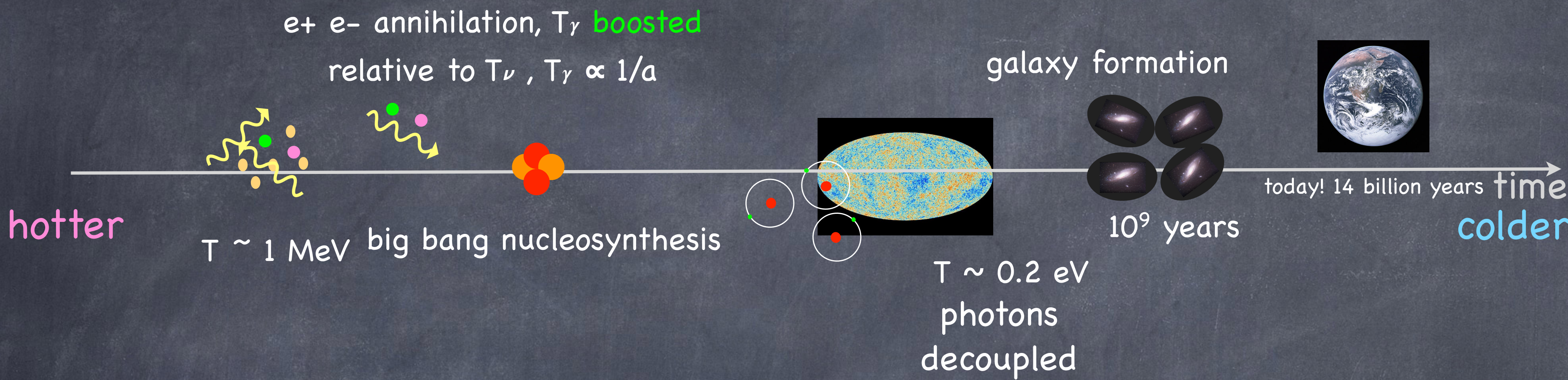


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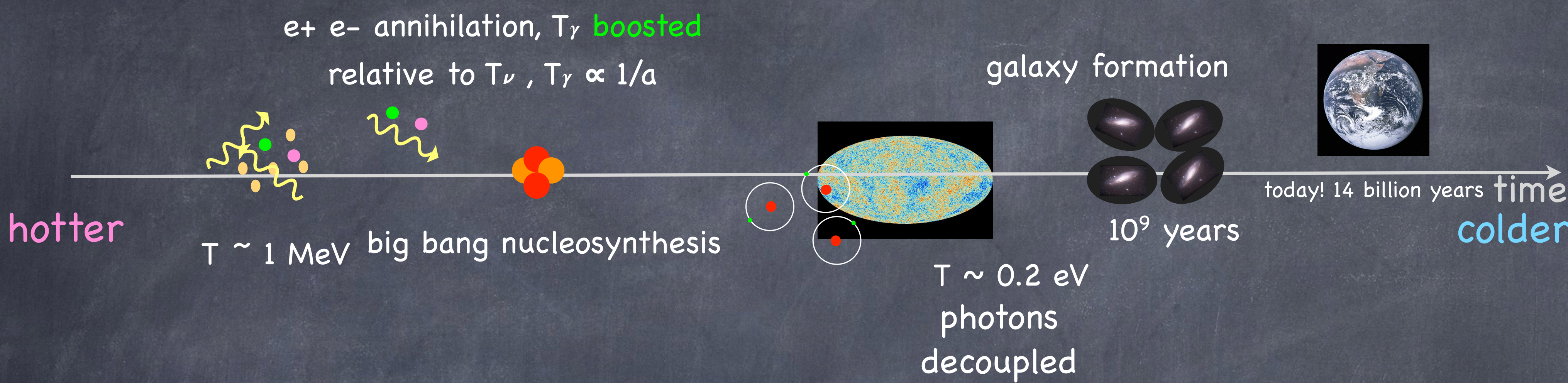


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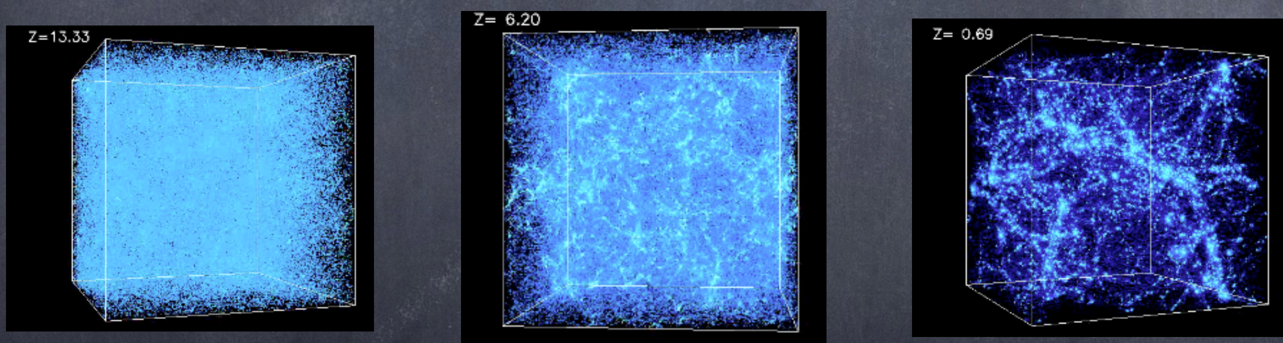
→ Large-scale Structure

# Neutrinos in Large-scale structure




time

(Kravtsov)

# Massive neutrinos and linear structure growth

The gravitational evolution of large-scale structure is different for fast and slow moving particles

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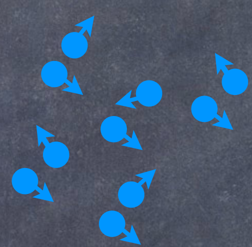
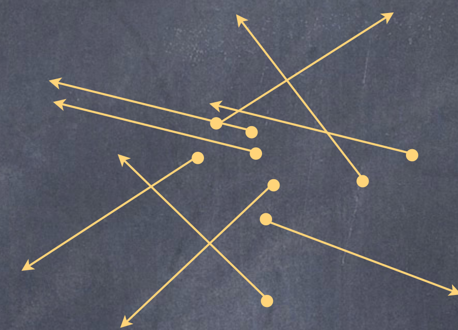


(clump easily)



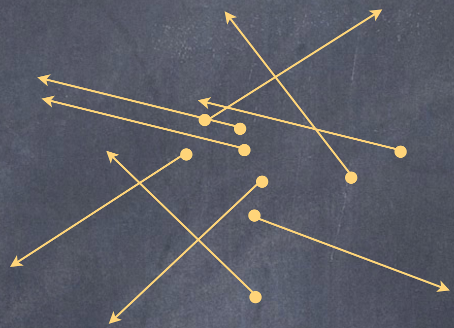
(don't clump easily)

# Massive neutrinos and linear structure growth

The gravitational evolution of large-scale structure is different for fast and slow moving particles

(clump easily)

baryons and cold dark matter



(don't clump easily)

neutrinos (or other exotic light dark matter)

# Massive neutrinos and linear structure growth

small-scale density perturbations don't retain neutrinos

cold dark matter and baryons density perturbation growing

neutrino density perturbation decaying

time

$$\frac{\delta\rho_c}{\rho_c}$$

$$\frac{\delta\rho_\nu}{\rho_\nu}$$

# Massive neutrinos and linear structure growth

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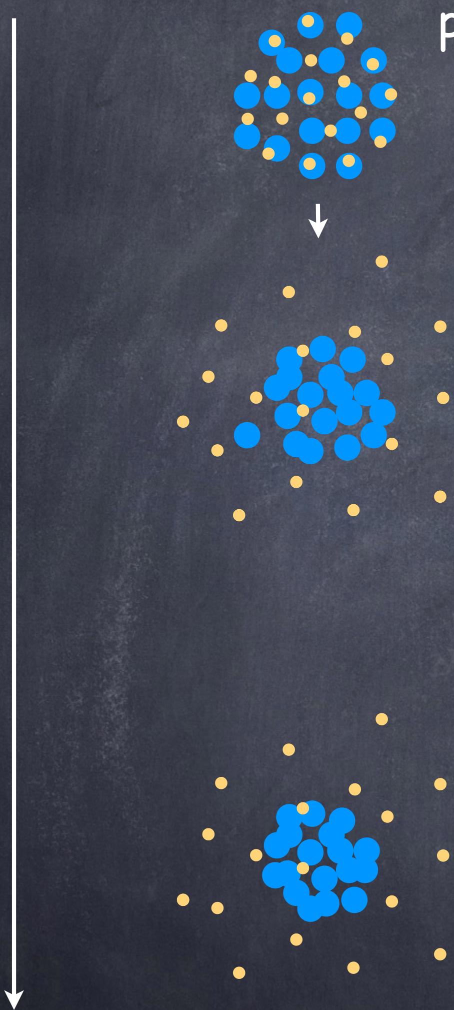
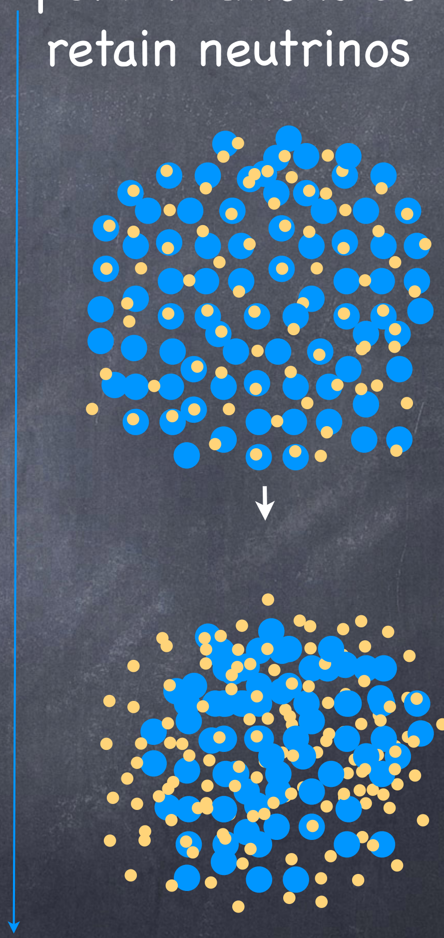


time

cold dark matter, baryons and neutrinos growing together

$\frac{\delta\rho_\nu}{\rho_\nu}$ $\frac{\delta\rho_c}{\rho_c}$

large-scale density perturbations do retain neutrinos



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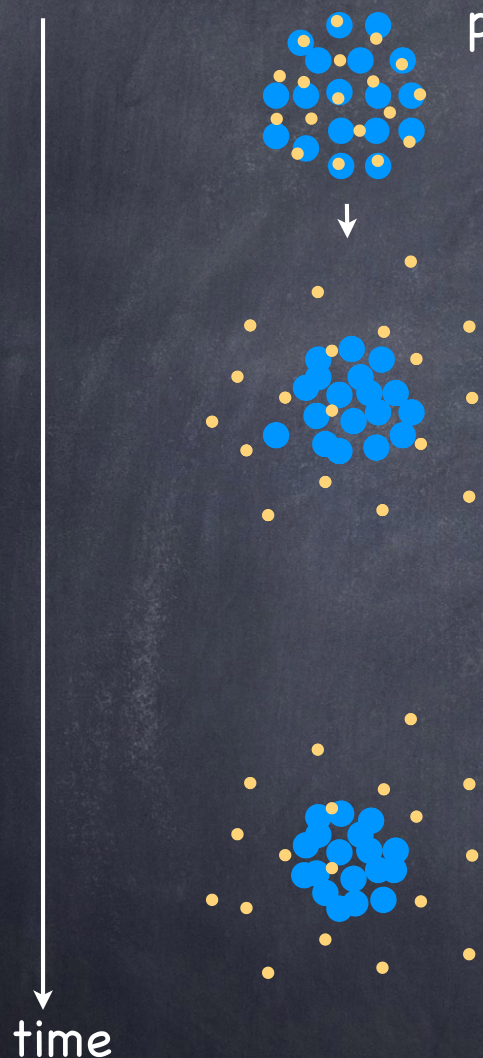


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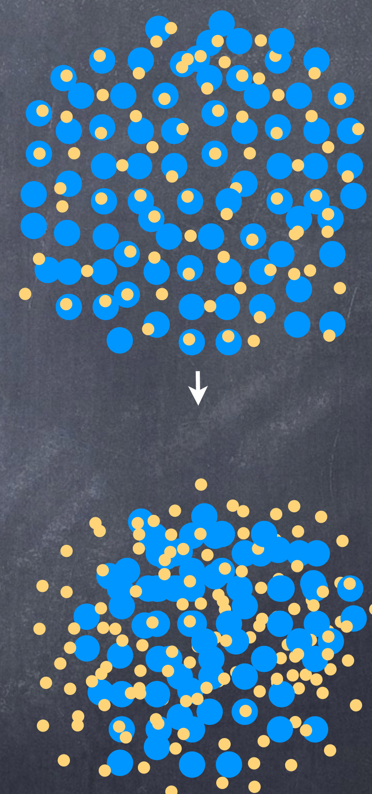

Growth of matter perturbations is scale-dependent

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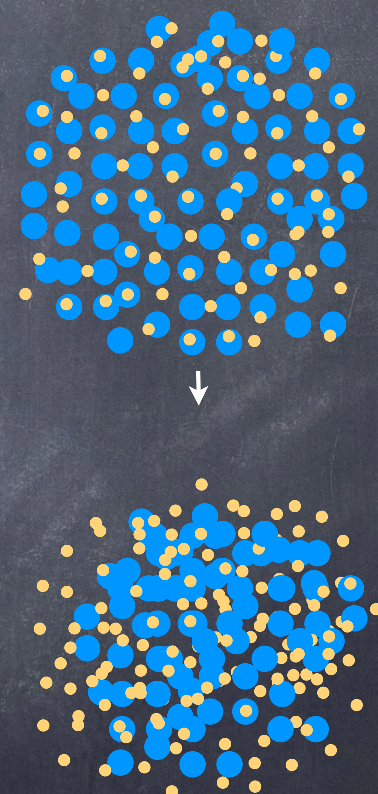

time

## Growth of matter perturbations is scale-dependent

Relevant scale:

Typical distance a neutrino can travel in a Hubble time

$\lambda_{fs} \sim u_\nu/H$

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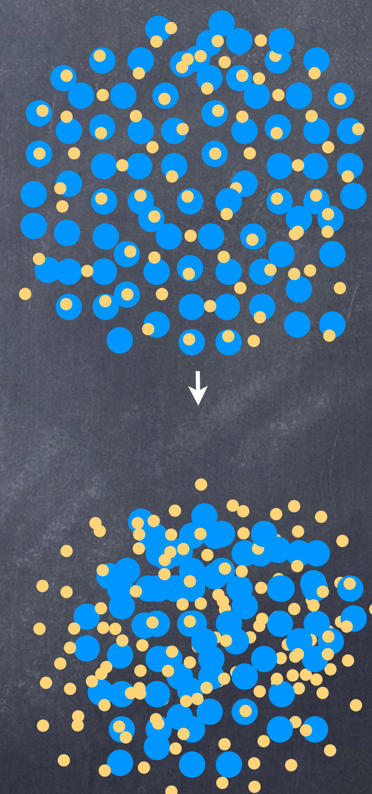

time

**Growth of matter perturbations is scale-dependent**

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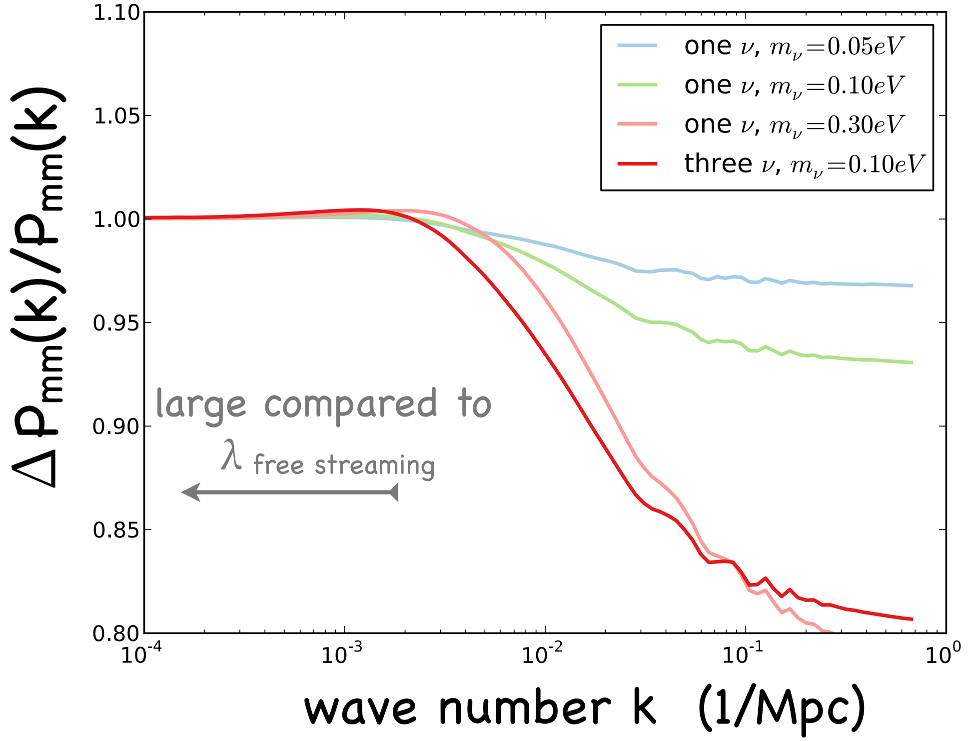
"free-streaming scale"

# Scale-dependent growth

change in typical amplitude of $\delta_m(k)$ from $m_\nu \neq 0$





Bond, Efstathiou, Silk 1980

Hu, Eisenstein, Tegmark 1998

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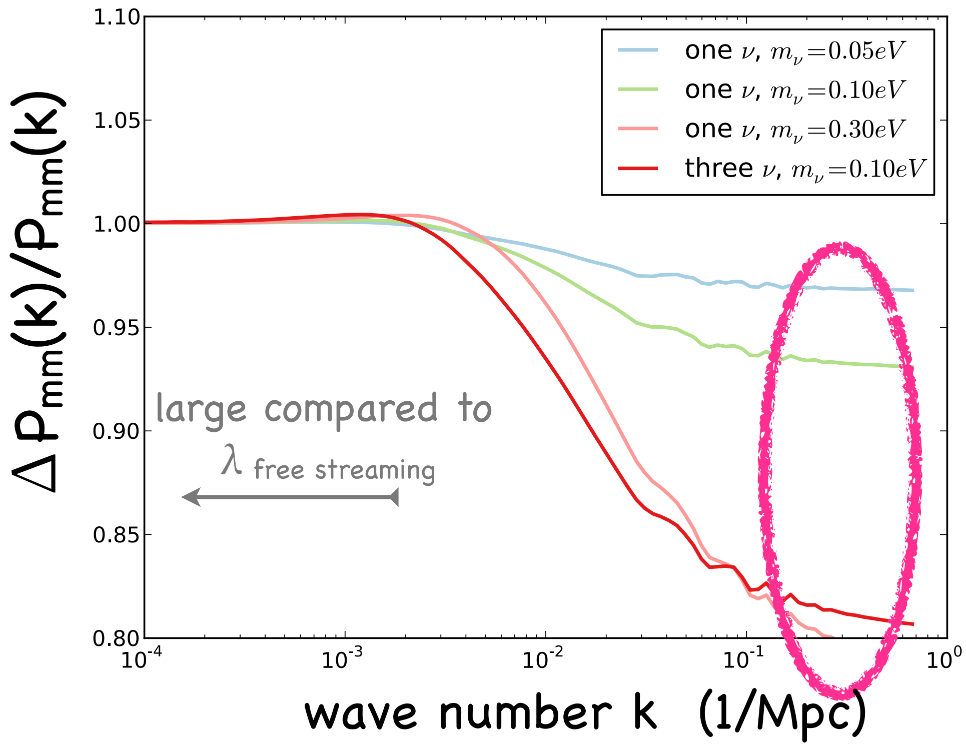
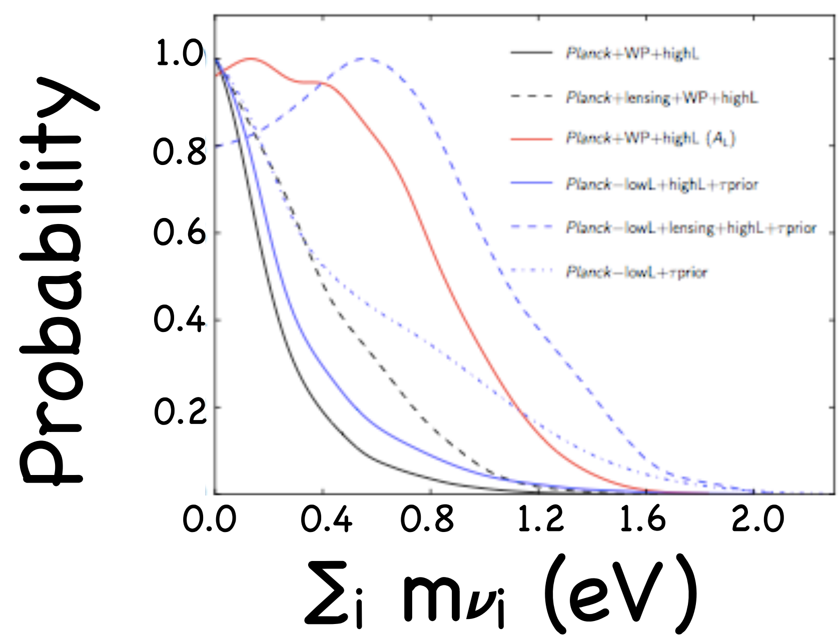



cosmological constraints!

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- Suppressed matter power spectrum (test via lensing, galaxy power spectra)

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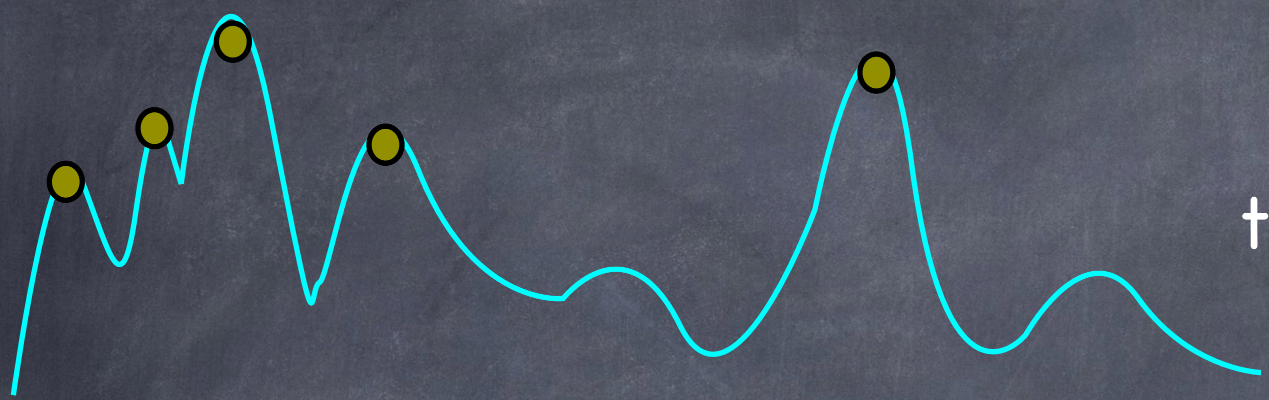
- new! Scale-dependent halo bias (ML 2014)

# Scale-dependent halo bias from massive neutrinos

# Scale-dependent bias — main idea:



halos are biased tracers of the matter density field

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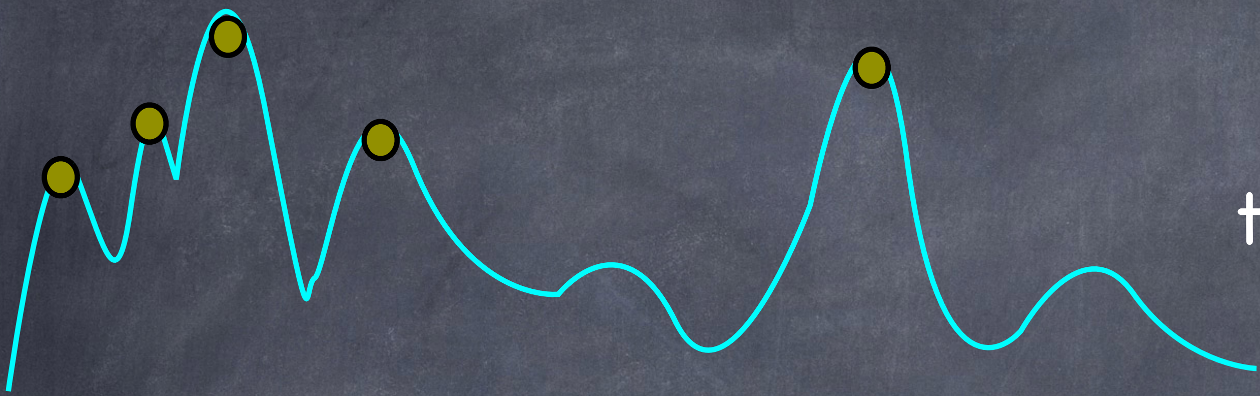
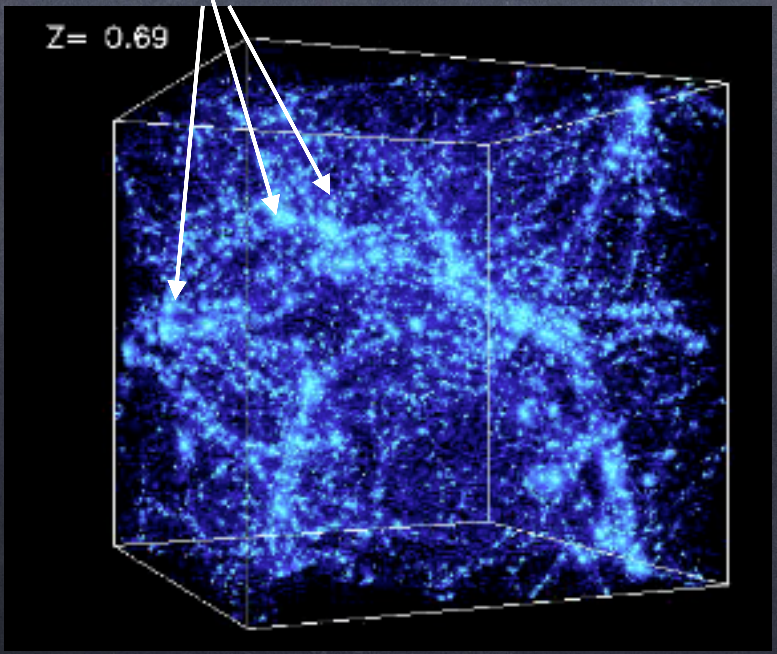


halos are biased tracers of the matter density field

(these nodes are cold dark matter halos)




(Kravtsov)

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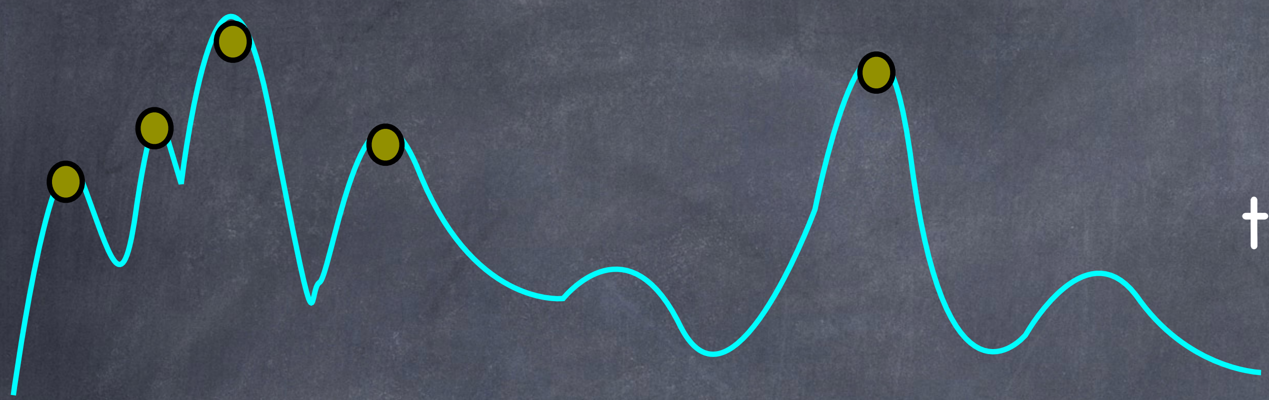

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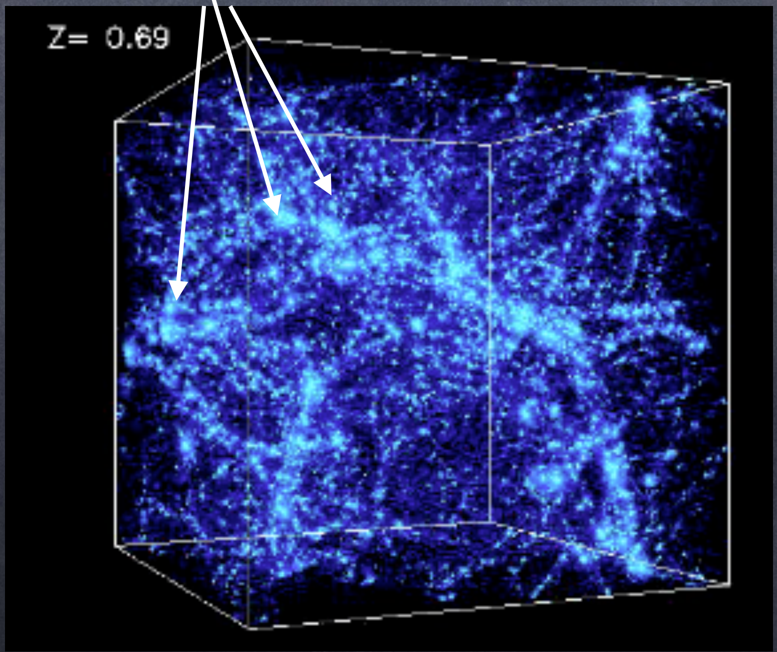


(Kravtsov)

i.e. gravitationally bound blobs of dark matter where galaxies and clusters of galaxies live

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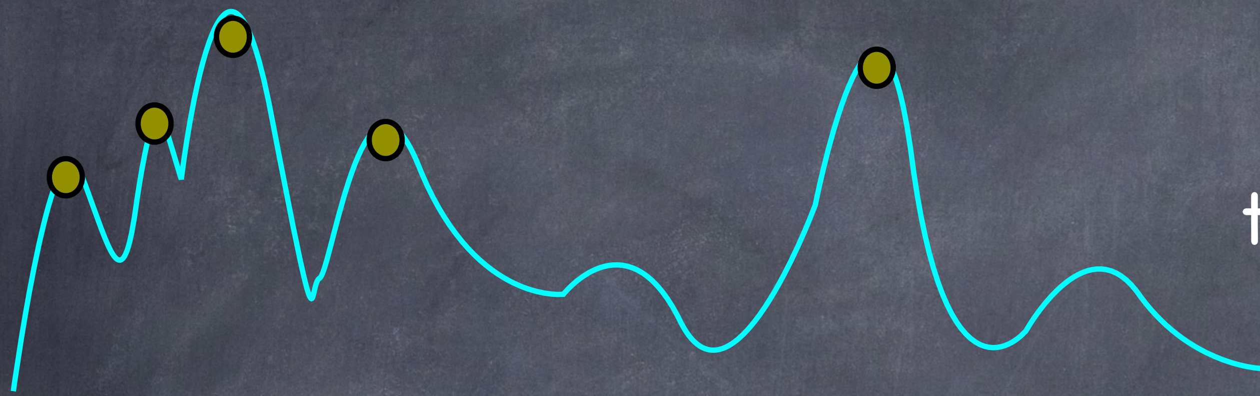

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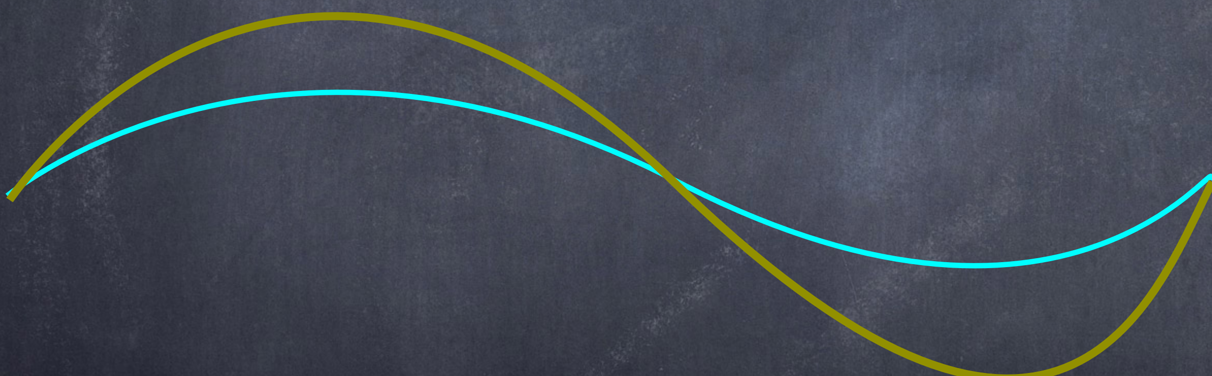

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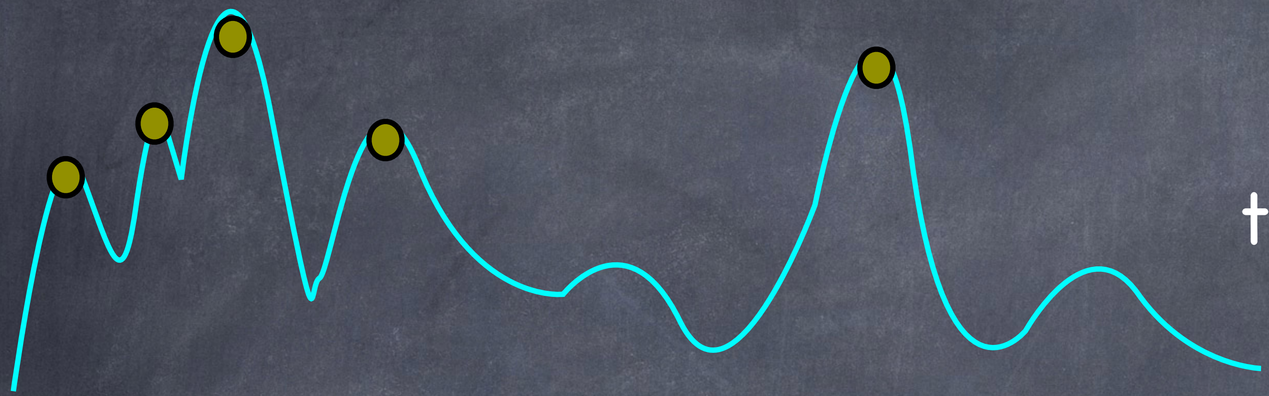


halos are biased tracers of the matter density field

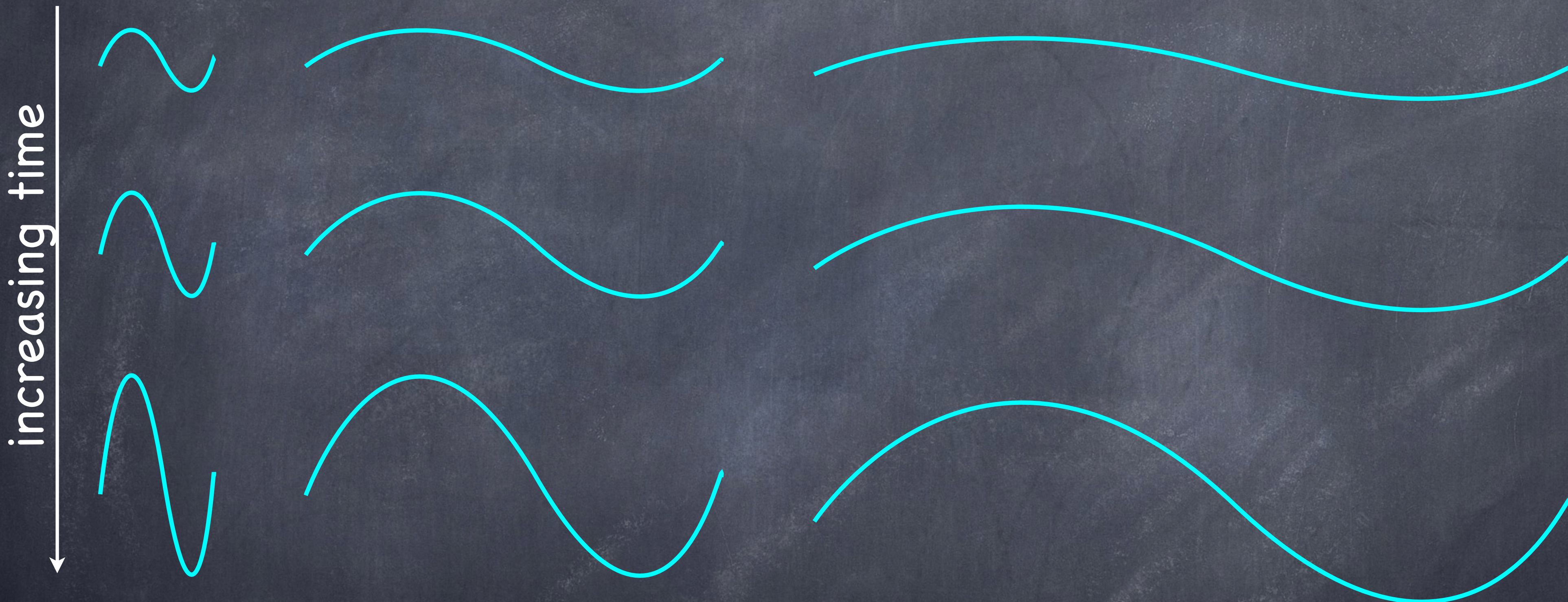
the number density of halos is modulated by long-wavelength fluctuations in the matter density field

$$\frac{\delta n}{n} \equiv b \left.\frac{\delta \rho}{\rho}\right|_{\text{long-wavelength}}$$

b is the halo bias

# Scale-dependent bias — main idea:

In a universe with CDM only, the linear evolution of matter fluctuations is independent of their wavelength




$$\frac{\delta\rho}{\rho}(k, z_{\rm final}) \propto D(z_{\rm final})\,\frac{\delta\rho}{\rho}(k, z_{\rm initial})$$

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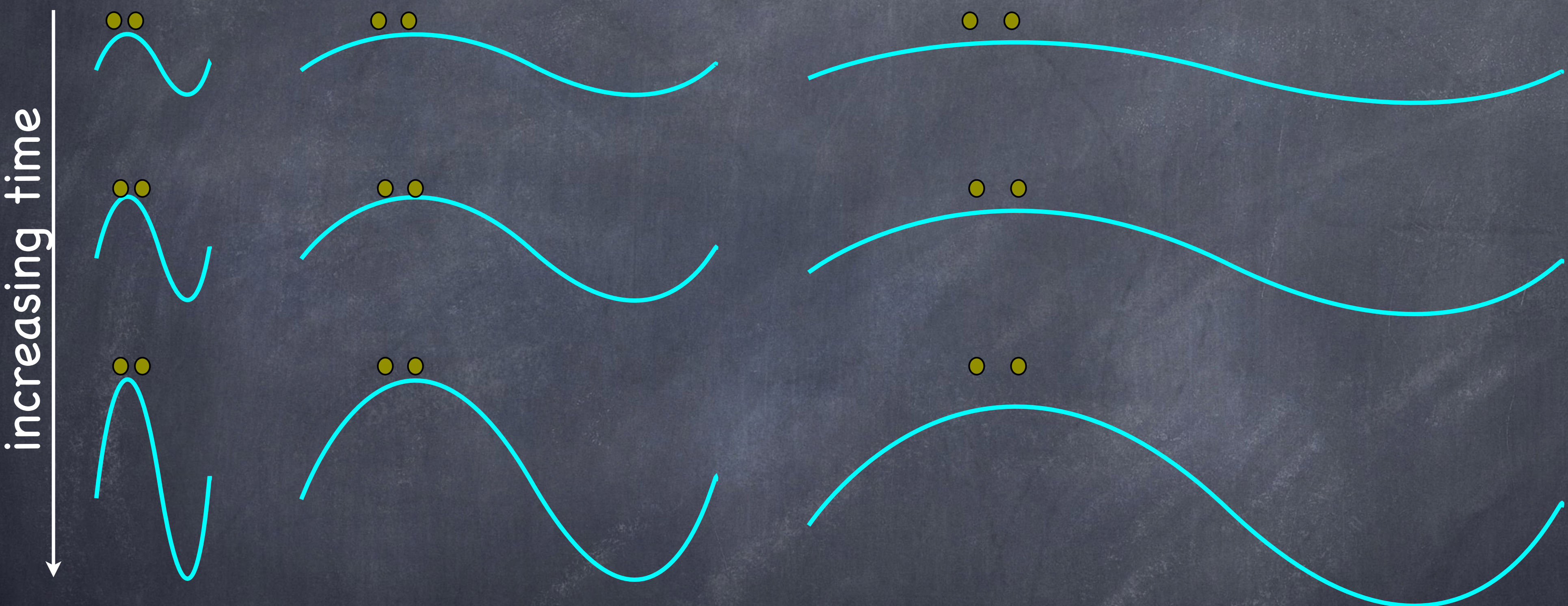


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halos can't tell the wavelength of the background matter density perturbation

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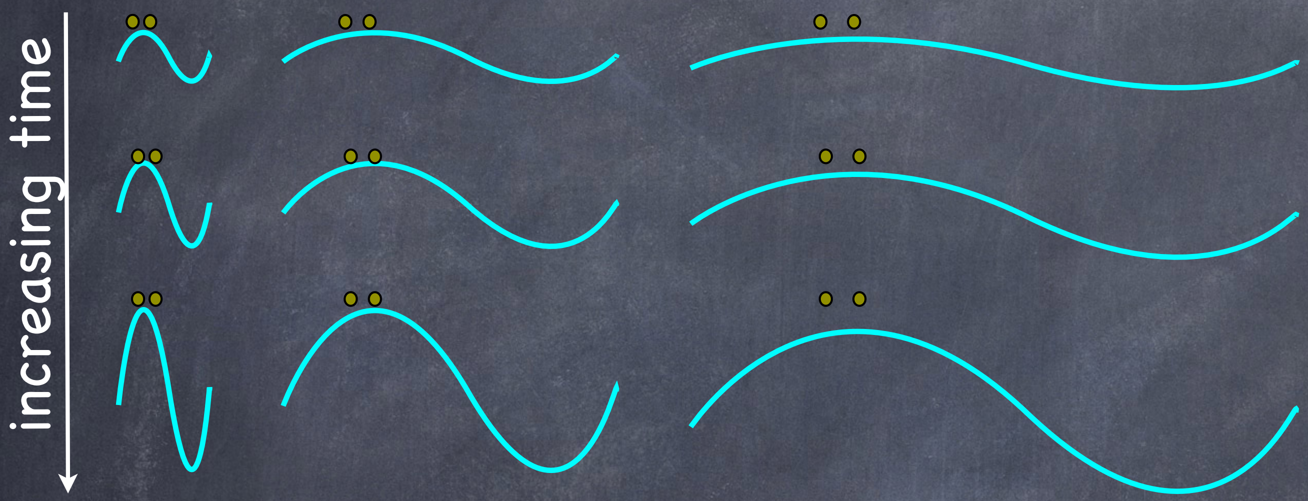


halos can't tell the wavelength of the background matter density perturbation

↓

the effect of $\frac{\delta\rho}{\rho}$ on the halo field (the linear bias) is independent of k

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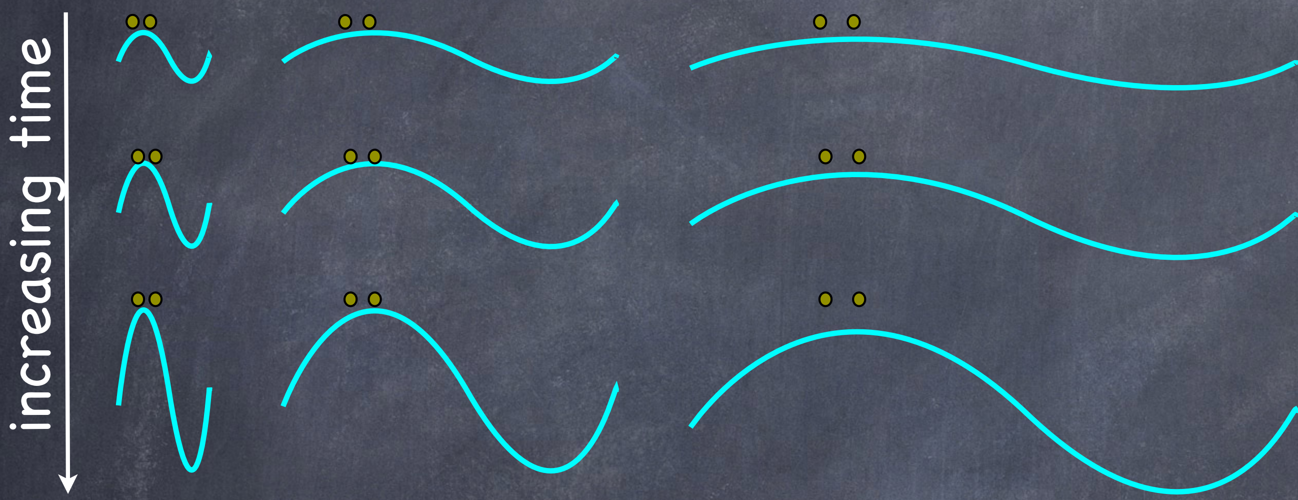



halos can't tell the wavelength of the background matter density perturbation

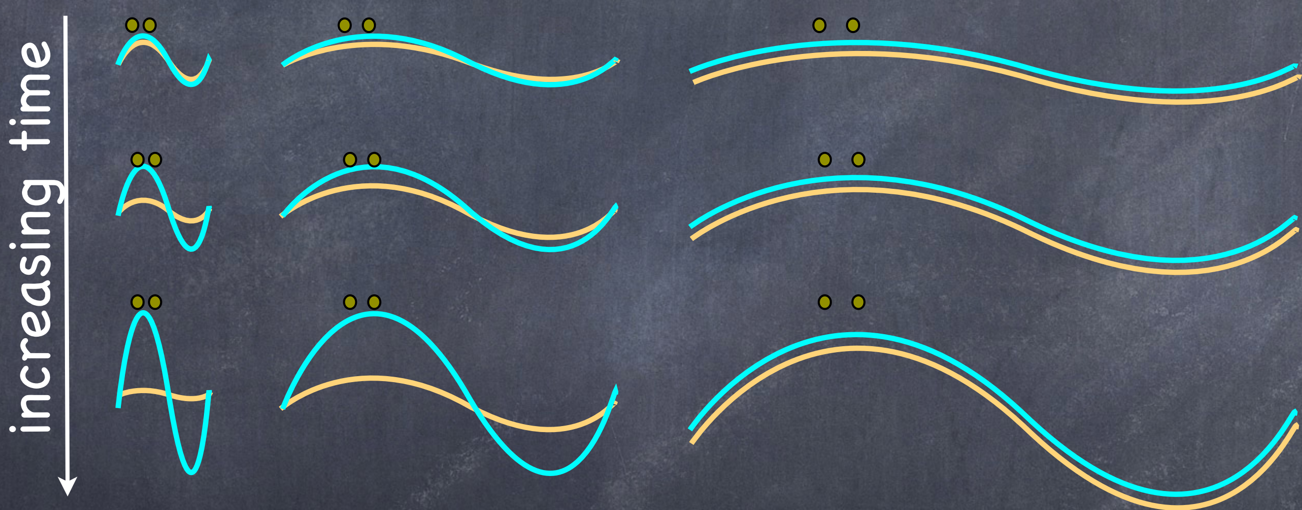
↓

the effect of $\frac{\delta\rho}{\rho}$ on the halo field (the linear bias) is independent of k

massive neutrinos break this

halo bias can depend on k

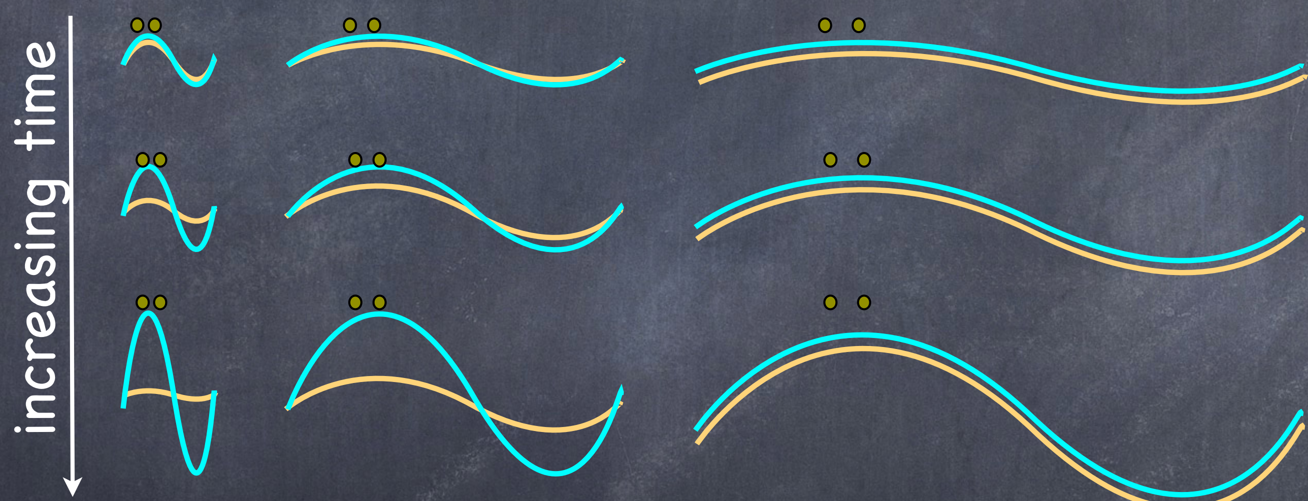
# Scale-dependent bias – main idea:




halos
neutrinos
cold dark matter

# Scale-dependent bias — main idea:

WANT: estimate of k-dependence of the halo bias caused by massive neutrinos




halos
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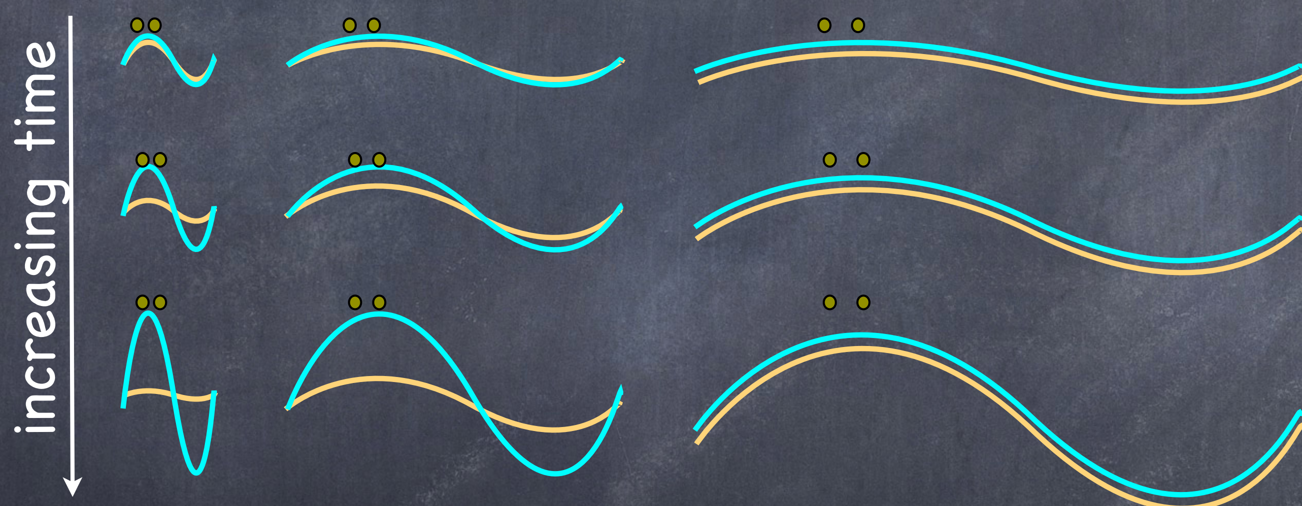



halos
neutrinos
cold dark matter

( see also Hui & Parfrey 2008; Parfrey, Hui, Sheth 2011;)

# Scale-dependent bias

The scale-dependent growth of density perturbations causes halo bias to be scale dependent

# Scale-dependent bias

The scale-dependent growth of density perturbations causes halo bias to be scale dependent

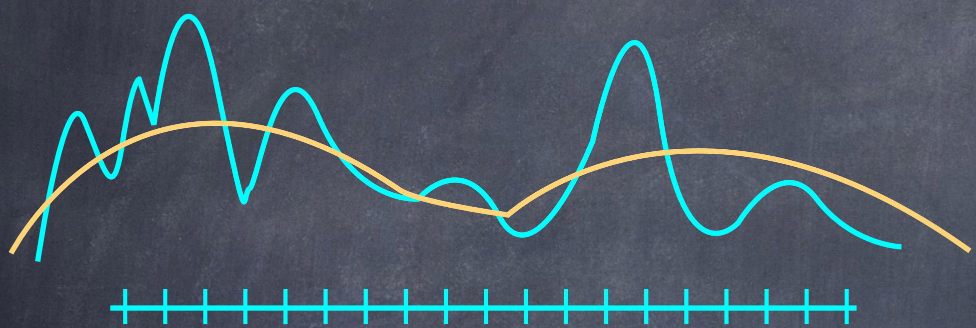
$$\frac{\delta n}{n}(k) = b\,\frac{\delta\rho_m}{\rho_m}(k) \longrightarrow \frac{\delta n}{n}(k) = b(k)\,\frac{\delta\rho_m}{\rho_m}(k)$$

# Prescription for calculating the halo bias in a universe with massive neutrinos

# Scale-dependent bias

## Prescription for calculating the halo bias

initial density field



(ML 2014)

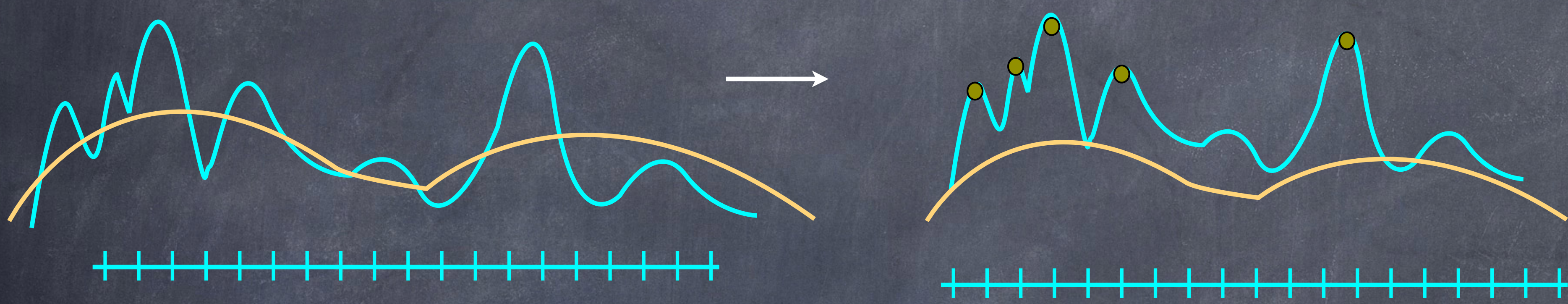
Gunn & Gott 1972
Press & Schechter 1974

# Scale-dependent bias

## Prescription for calculating the halo bias

initial density field

initial proto-halo distribution



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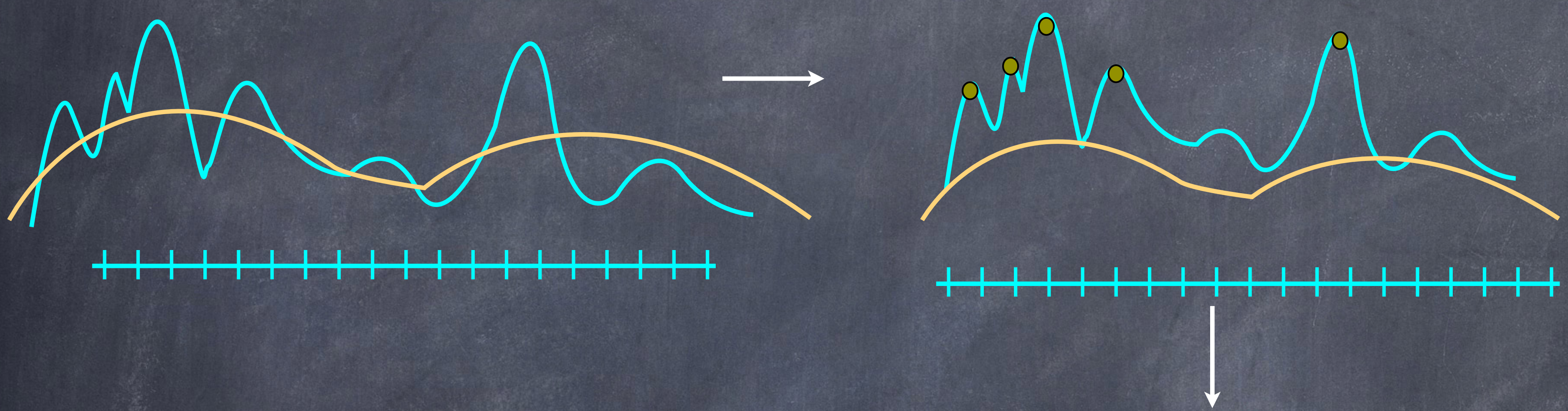
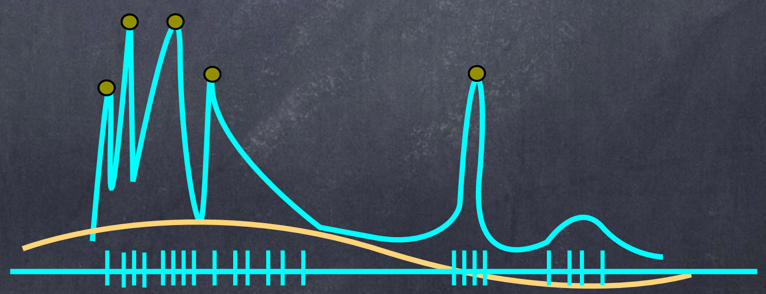


late time halo distribution



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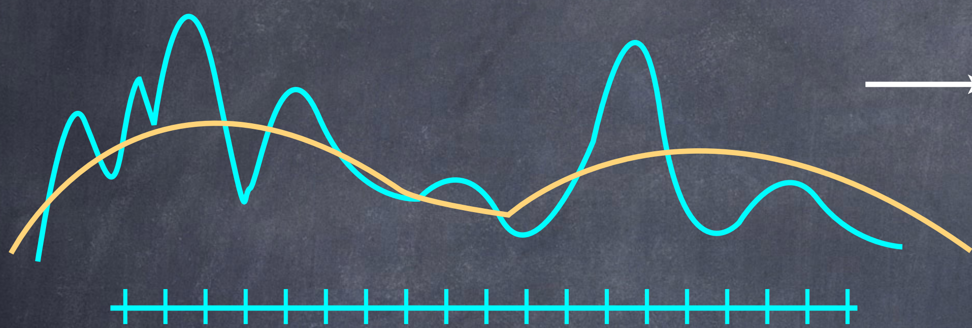

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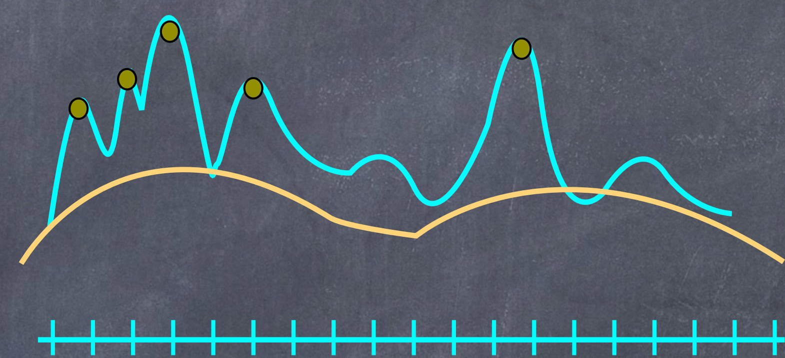

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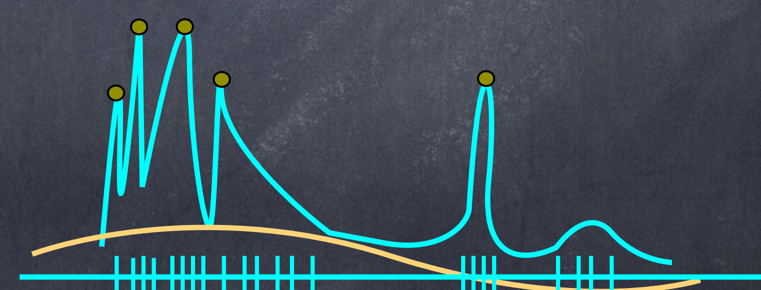

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(ML 2014)

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# Scale-dependent bias

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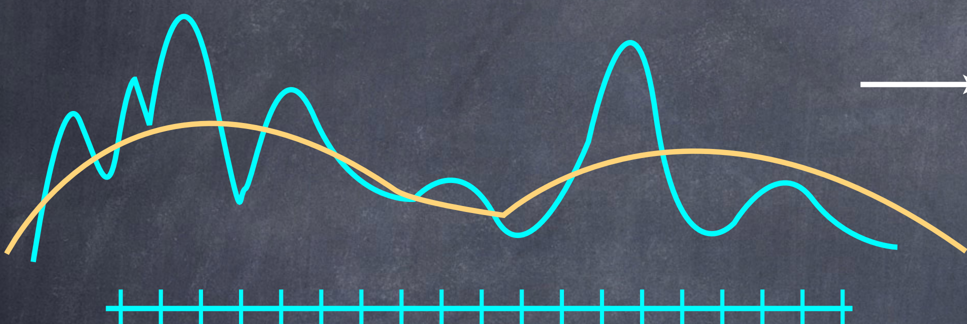

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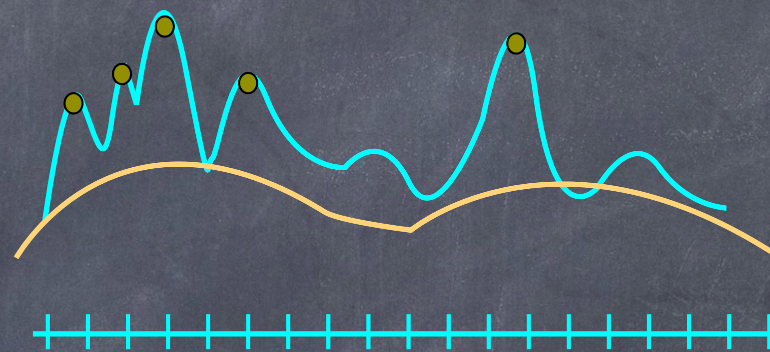
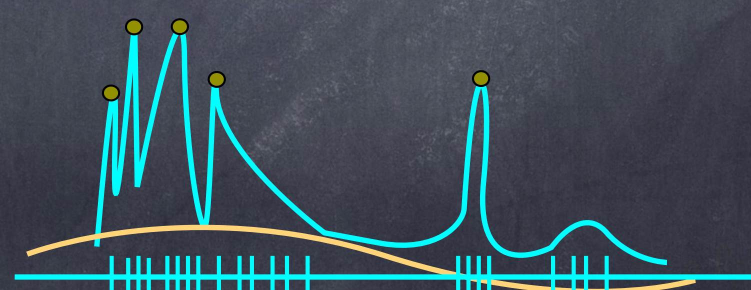


late time halo distribution



$$\frac{\delta n}{n} \equiv b \left.\frac{\delta \rho}{\rho}\right|_{\text{long-wavelength}}$$

want this!

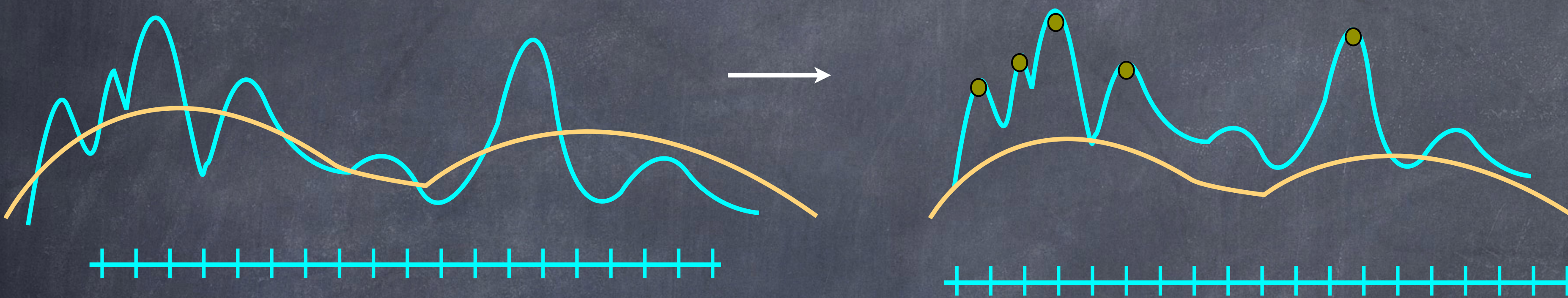
(ML 2014)

Gunn & Gott 1972
Press & Schechter 1974

# Scale-dependent bias

## Prescription for calculating the halo bias

initial density field — initial proto-halo distribution



(i) In this step, the scale-dependent evolution of density perturbations causes

$$\frac{\delta n}{n}_{\mathrm{Lagrangian}}(k) = b_{\mathrm{Lagrangian}}(k)\,\frac{\delta\rho_{\mathrm{cdm}}}{\rho_{\mathrm{cdm}}}(k)$$

(ML 2014)

# Scale-dependent bias

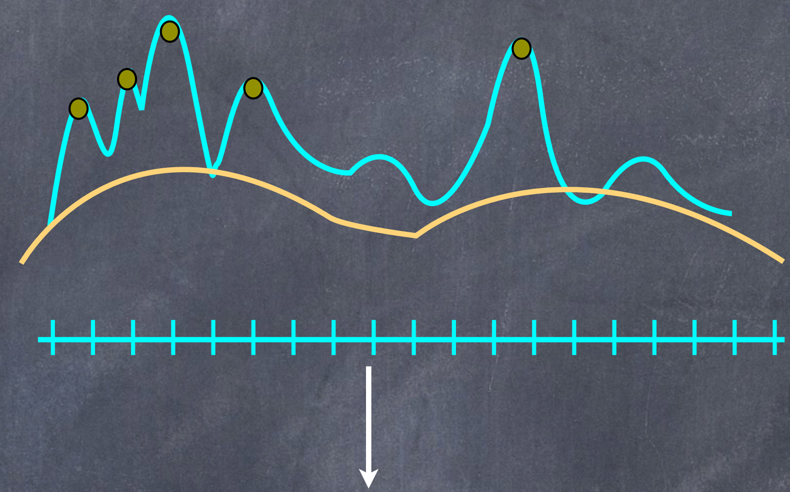
## Prescription for calculating the halo bias

(ii) In this step, the free streaming of neutrinos causes

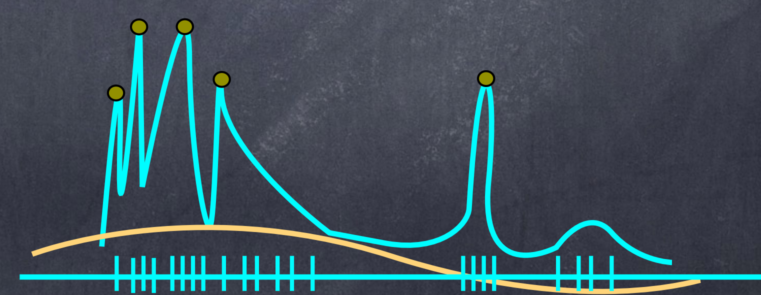
$$b(k) = \frac{\langle \delta_n(k)\delta_m(k) \rangle}{\langle \delta_m(k)\delta_m(k) \rangle}$$

$$= (1 + b_{Lagrangian}(k))\frac{\langle \delta_{cdm}(k)\delta_m(k) \rangle}{\langle \delta_m(k)\delta_m(k) \rangle}$$

initial proto-halo distribution



late time halo distribution



(ML 2014)

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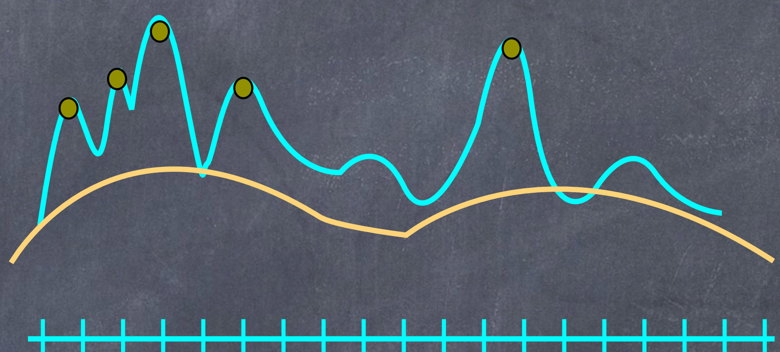

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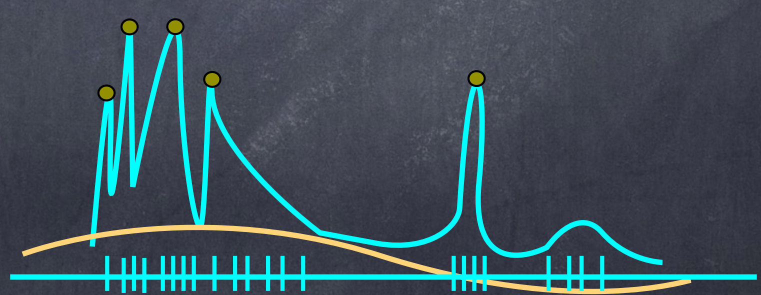

(i.e. halos trace CDM —> bias w.r.t total matter is scale-dependent)

(ML 2014)

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(i.e. halos trace CDM —> bias w.r.t total matter is scale-dependent)


see also Villaescusa-Navarro, Marulli, Viel, Branchini, Castorina 2013
Castorina, Sefusatti, Sheth, Villaescusa-Navarrow, Viel 2014
Biagetti, Desjacques, Kehagias, Riotto 2014

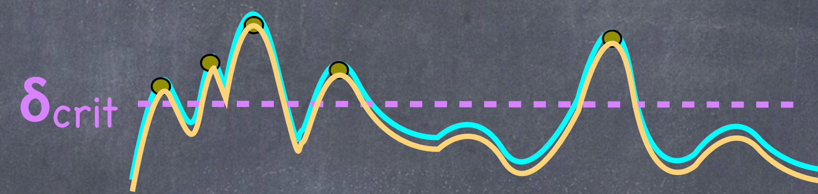
(ML 2014)

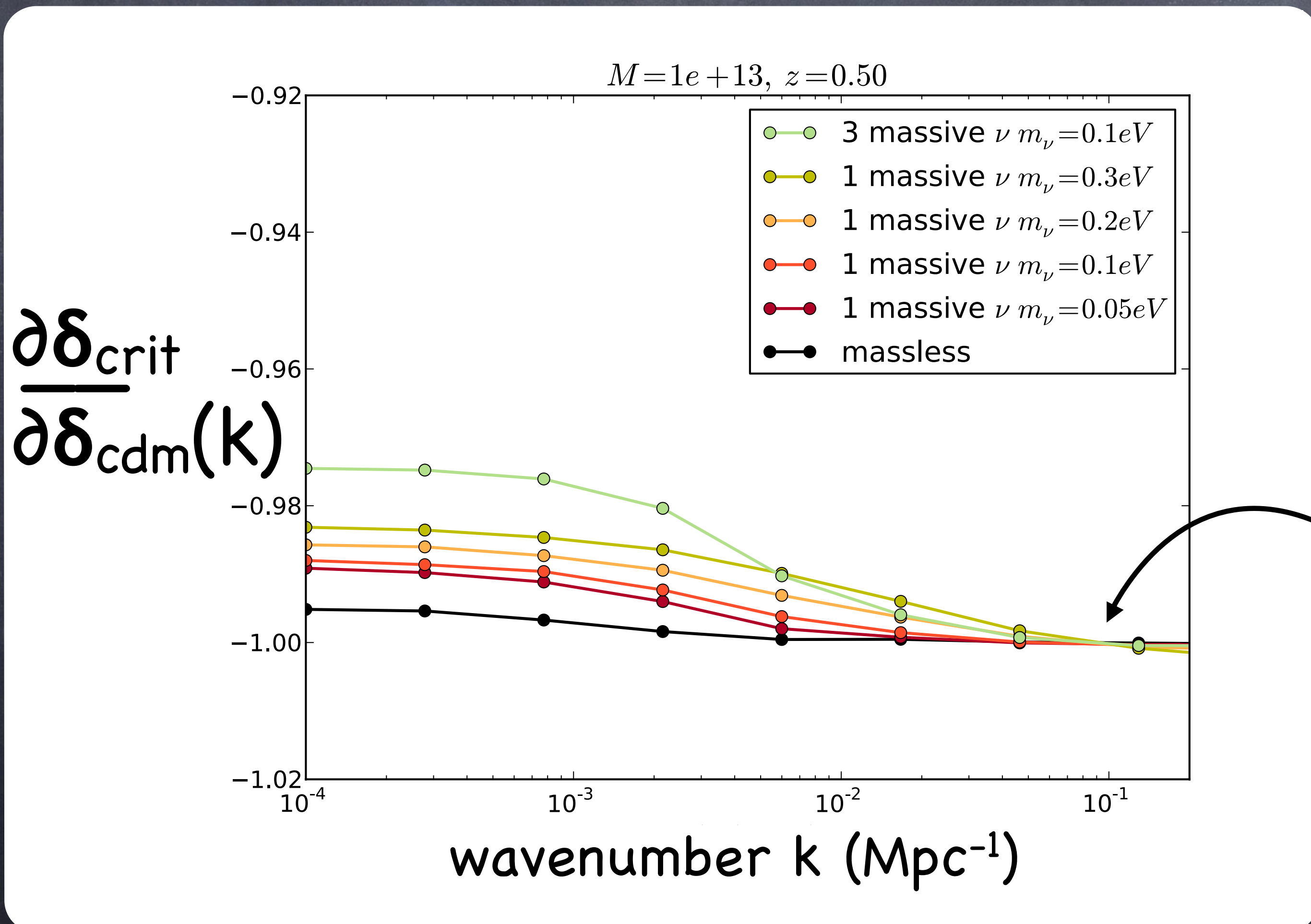
# Numerical estimates for scale-dependent halo bias

# Scale-dependent bias

## Numerical results for halo bias

Scale-dependent changes to $\delta_{crit}$



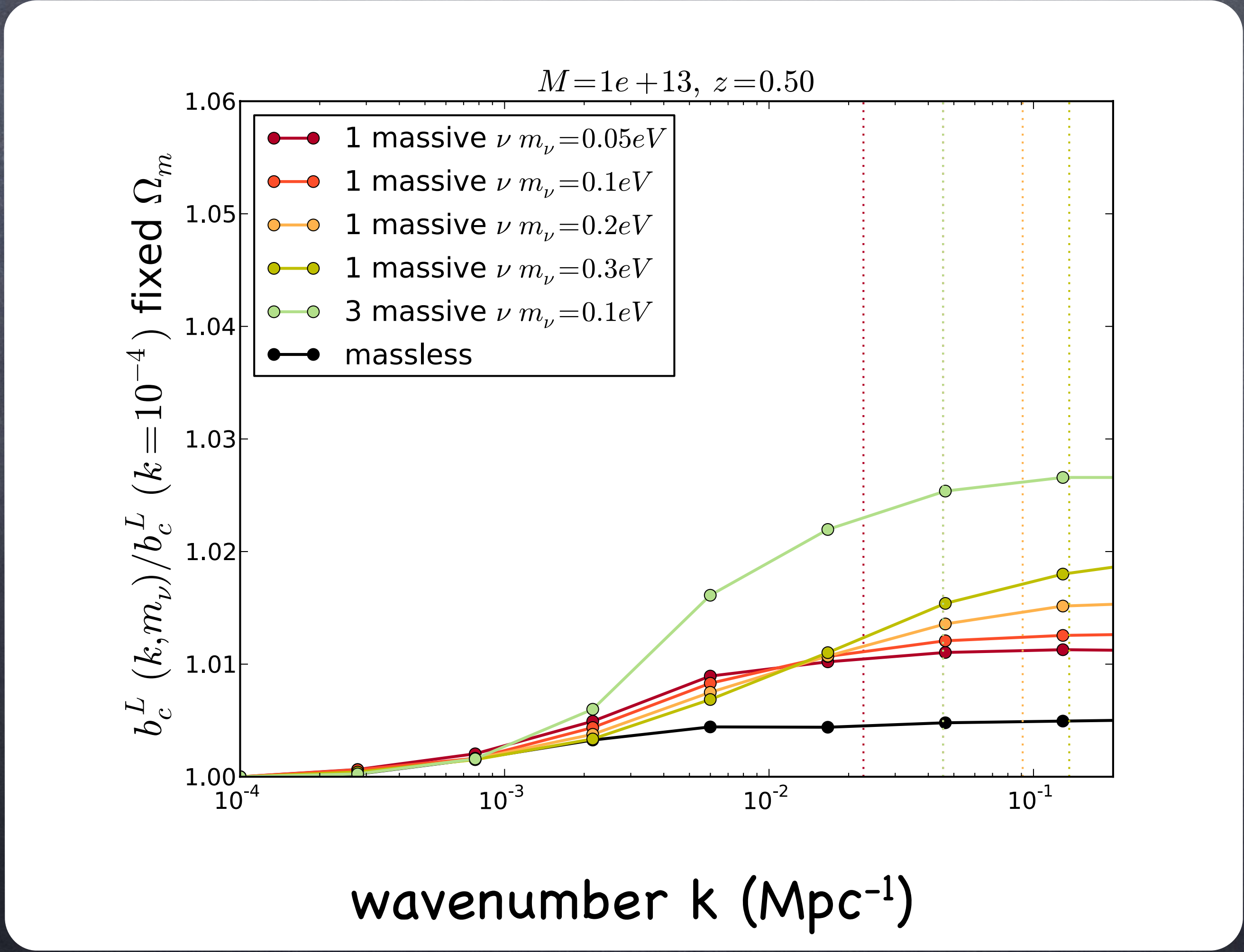

$\delta_{crit} = \delta_{crit} - \delta_{cdm}(k)$

(ML 2014)

# Scale-dependent bias

## Numerical results for halo bias

scale-dependent change to $$\delta n(k) = \frac{\partial n}{\partial \delta_{crit}} \frac{\partial \delta_{crit}}{\partial \delta_{cdm}(k)} \delta_{cdm}(k)$$




(Use Bhattacharya et al 2011 for $n(M|\ \delta_{crit})$)

(ML 2014)

# Scale-dependent bias

## Numerical results for halo bias

scale-dependent change to

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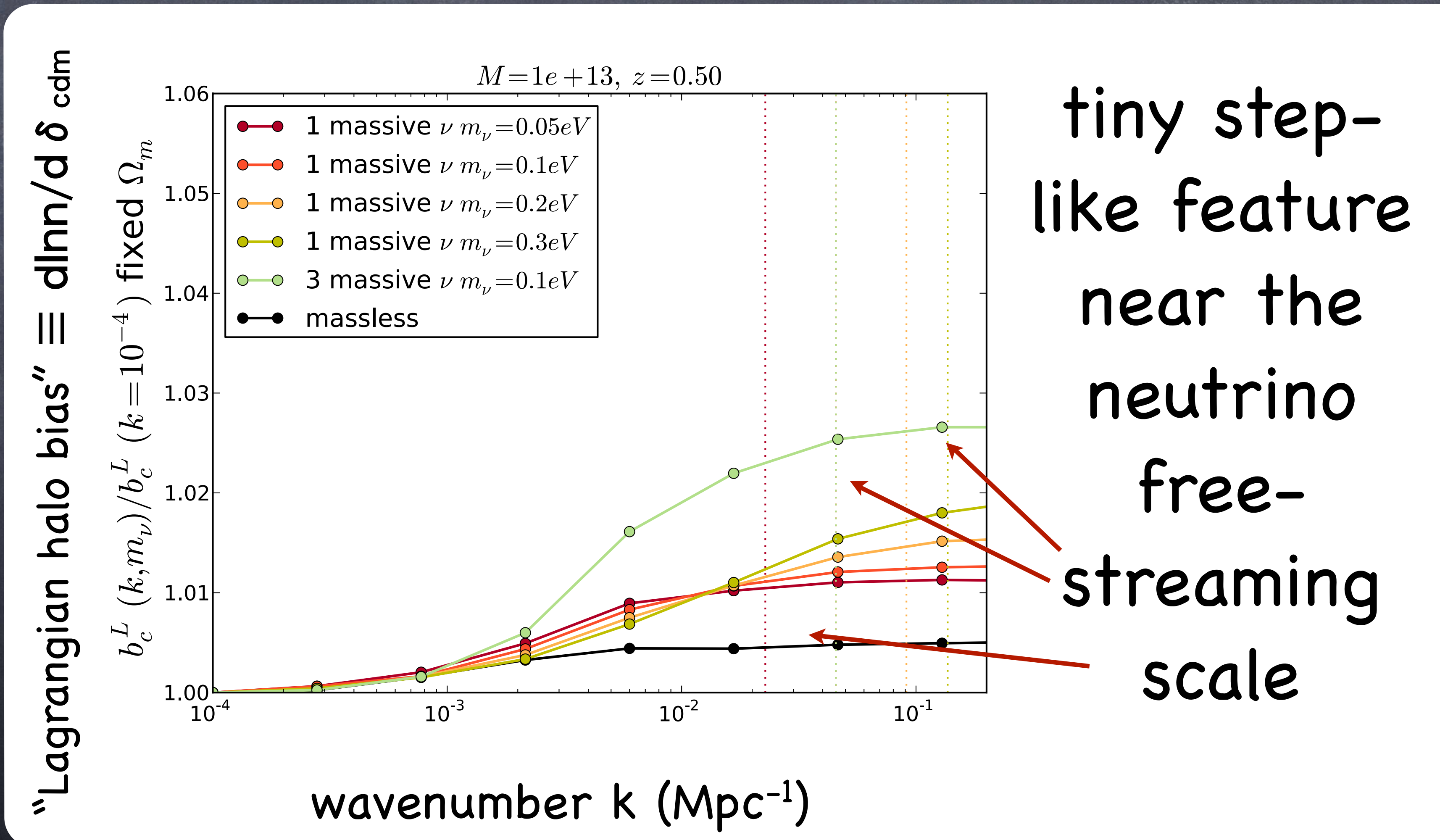



(Use Bhattacharya et al 2011 for n(M| $\delta_{crit}$)

(ML 2014)

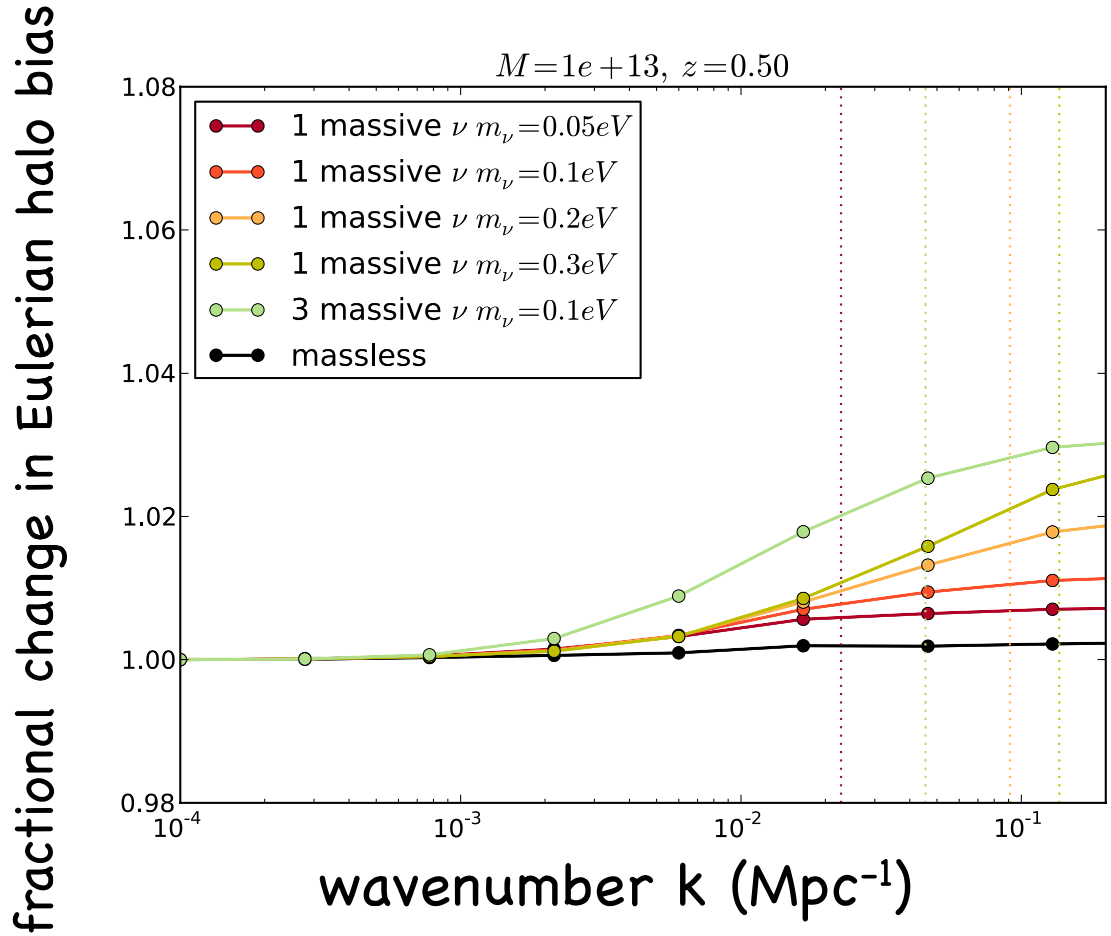
# Scale-dependent bias

## Numerical results for halo bias

scale-dependent change to final bias

$$\delta n(k)/n = b(k)\ \delta_{matter}(k)$$

$$b(k) = \sqrt{P_{hh}(k)/P_{mm}(k)}$$




(Use Bhattacharya et al 2011 for $n(M|\ \delta_{crit})$)

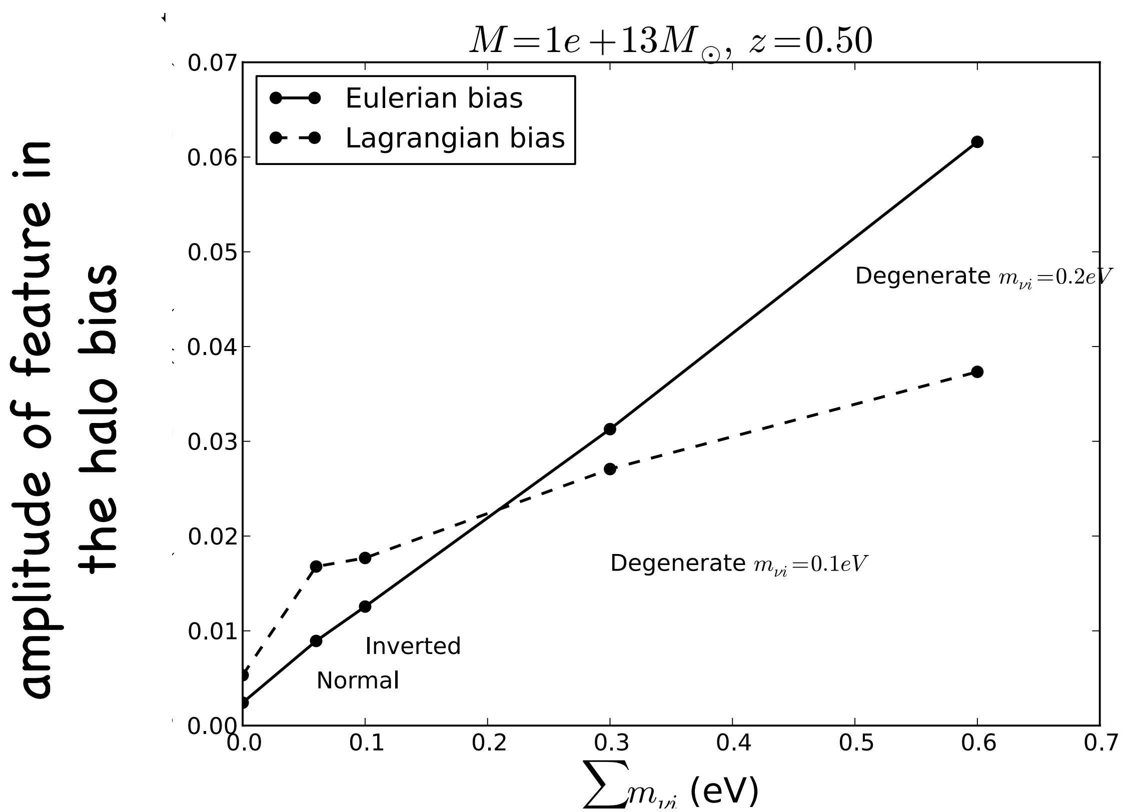
(ML 2014)

# Scale-dependent bias

## Numerical results for halo bias

scale-dependent change to final bias

$\delta n(k)/n = b(k)\ \delta_{matter}(k)$

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(ML 2014)

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scale-dependent change to final bias

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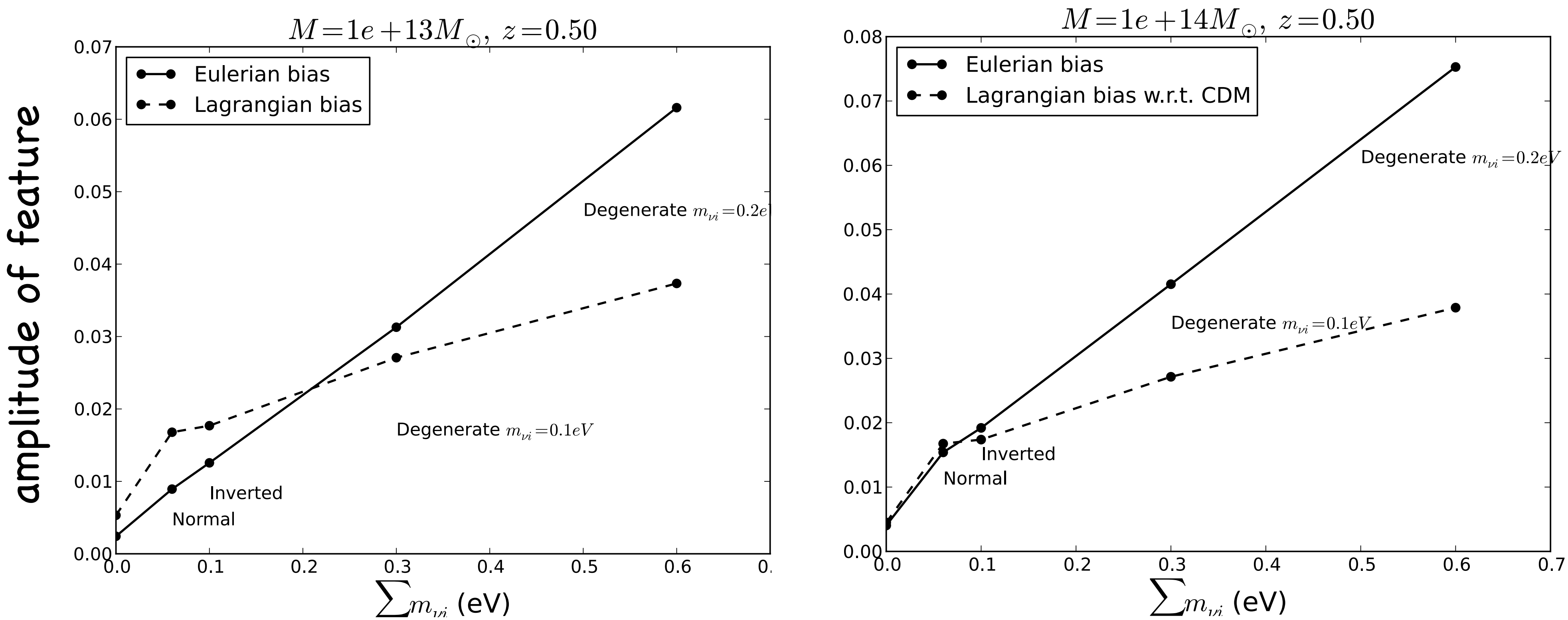


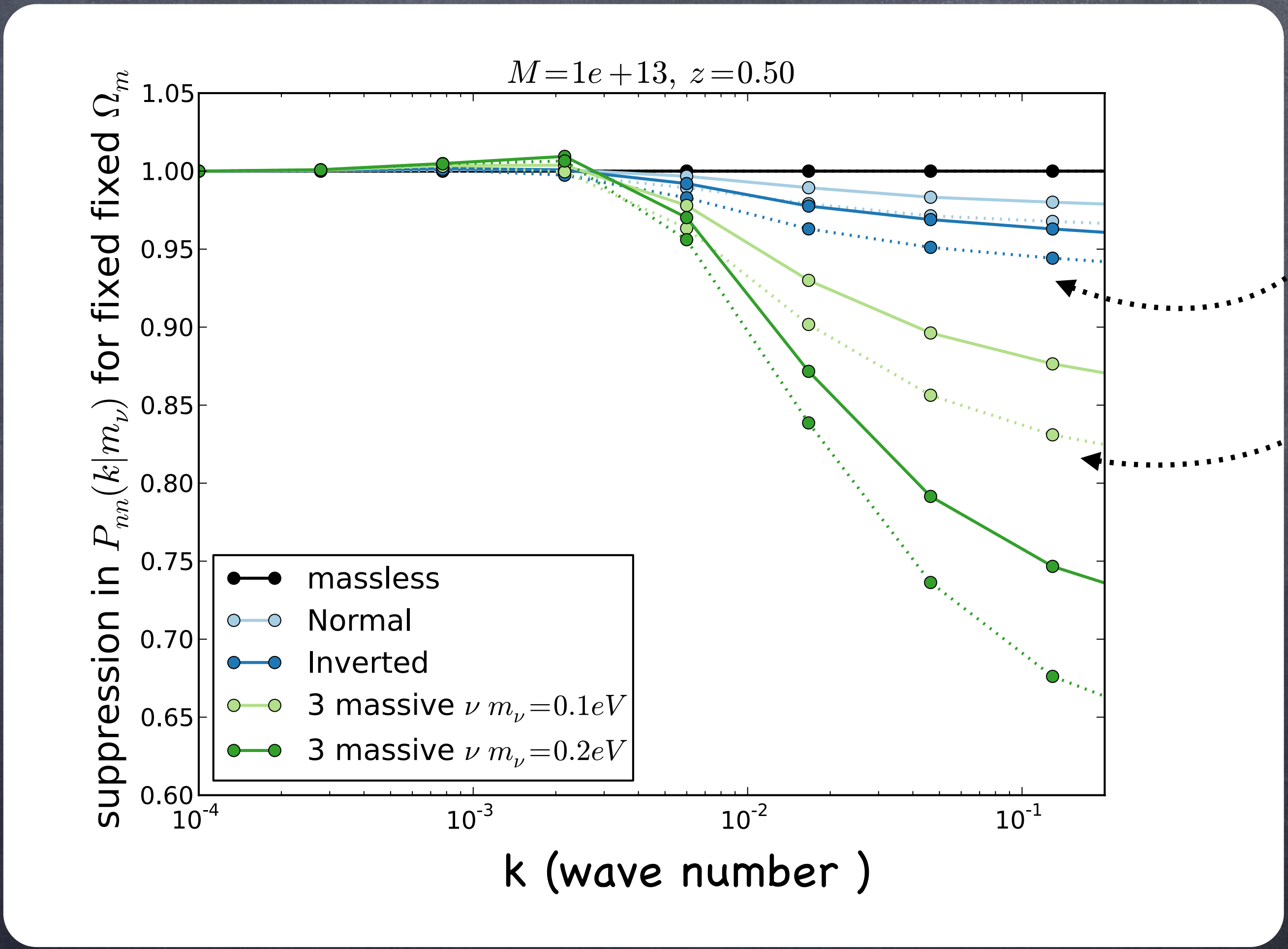

(ML 2014)

# Observational consequences of scale-dependent bias?

# Observational consequences of scale dependent bias?

matter power spectrum, or (incorrectly) assuming constant bias

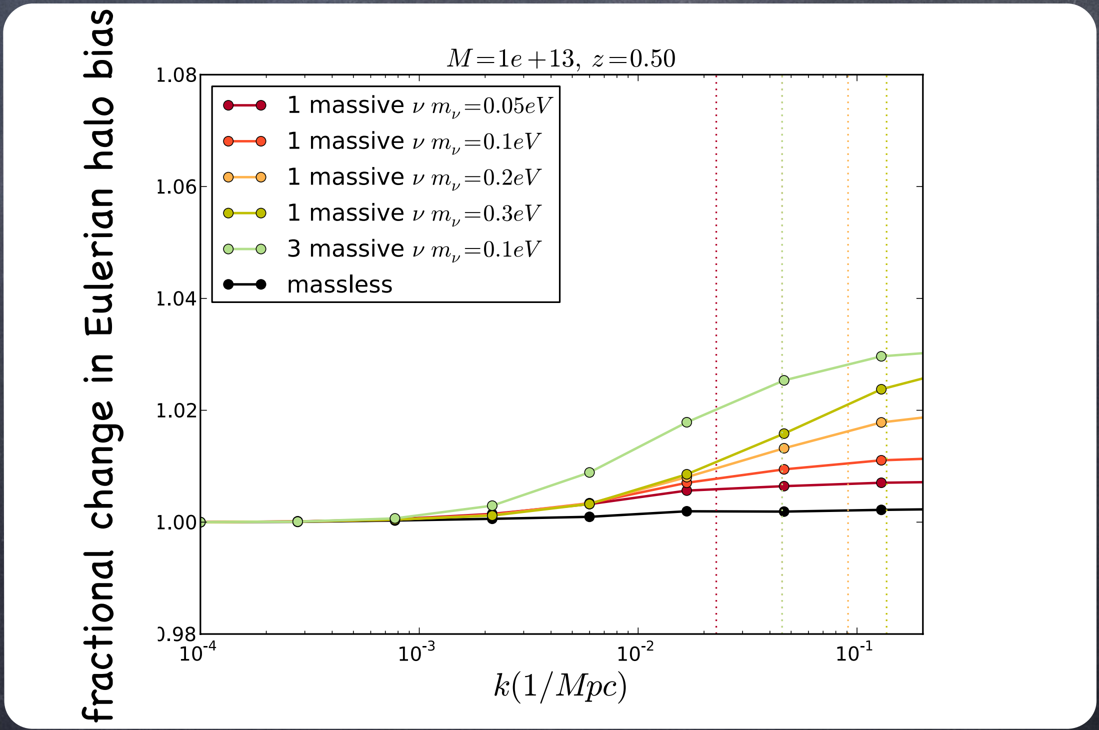
suppression in galaxy power spectrum less than in matter power spectrum



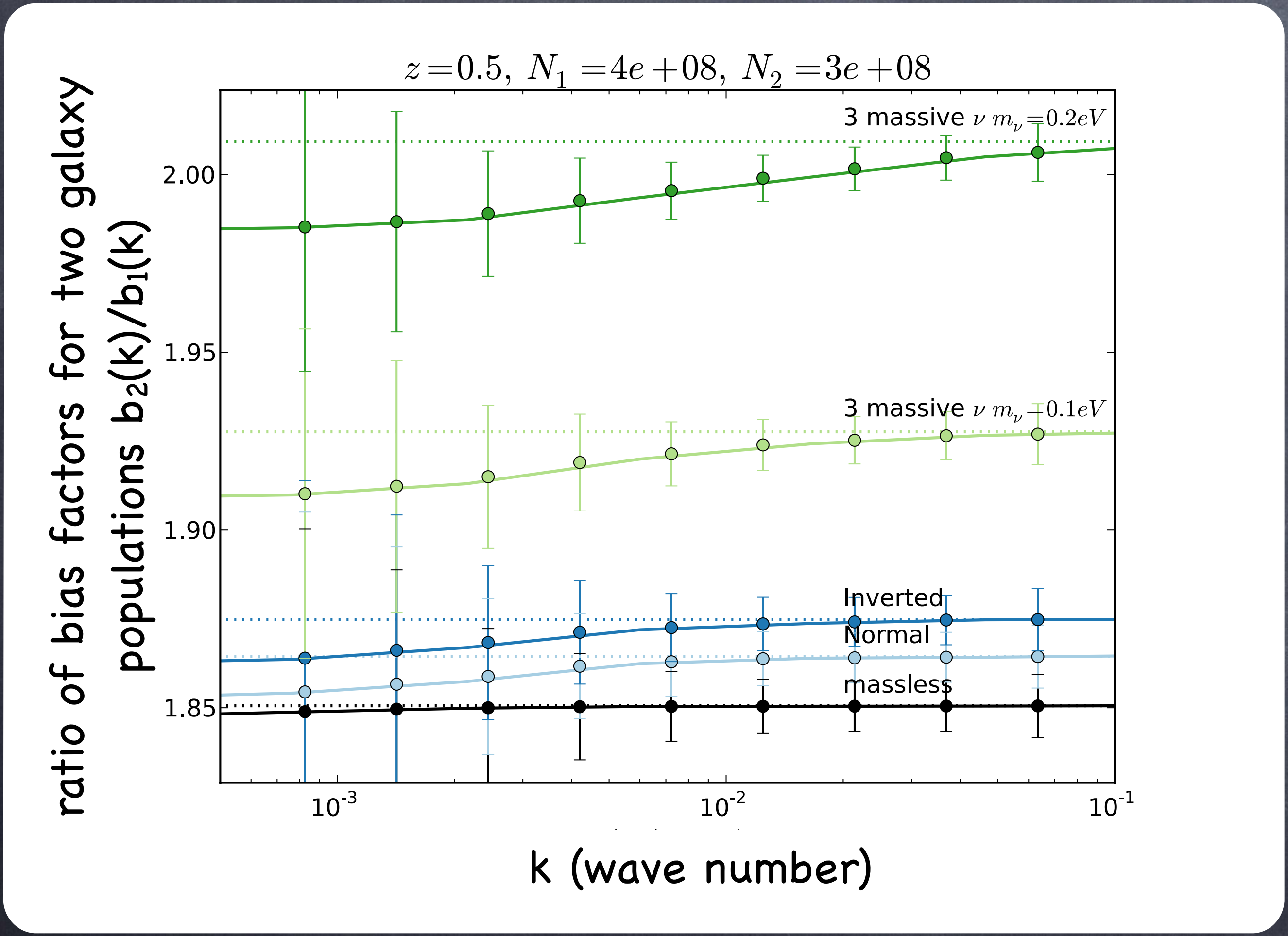

(ML 2014)

# Scale-dependent bias

But the scale-dependent halo bias is itself an observable!



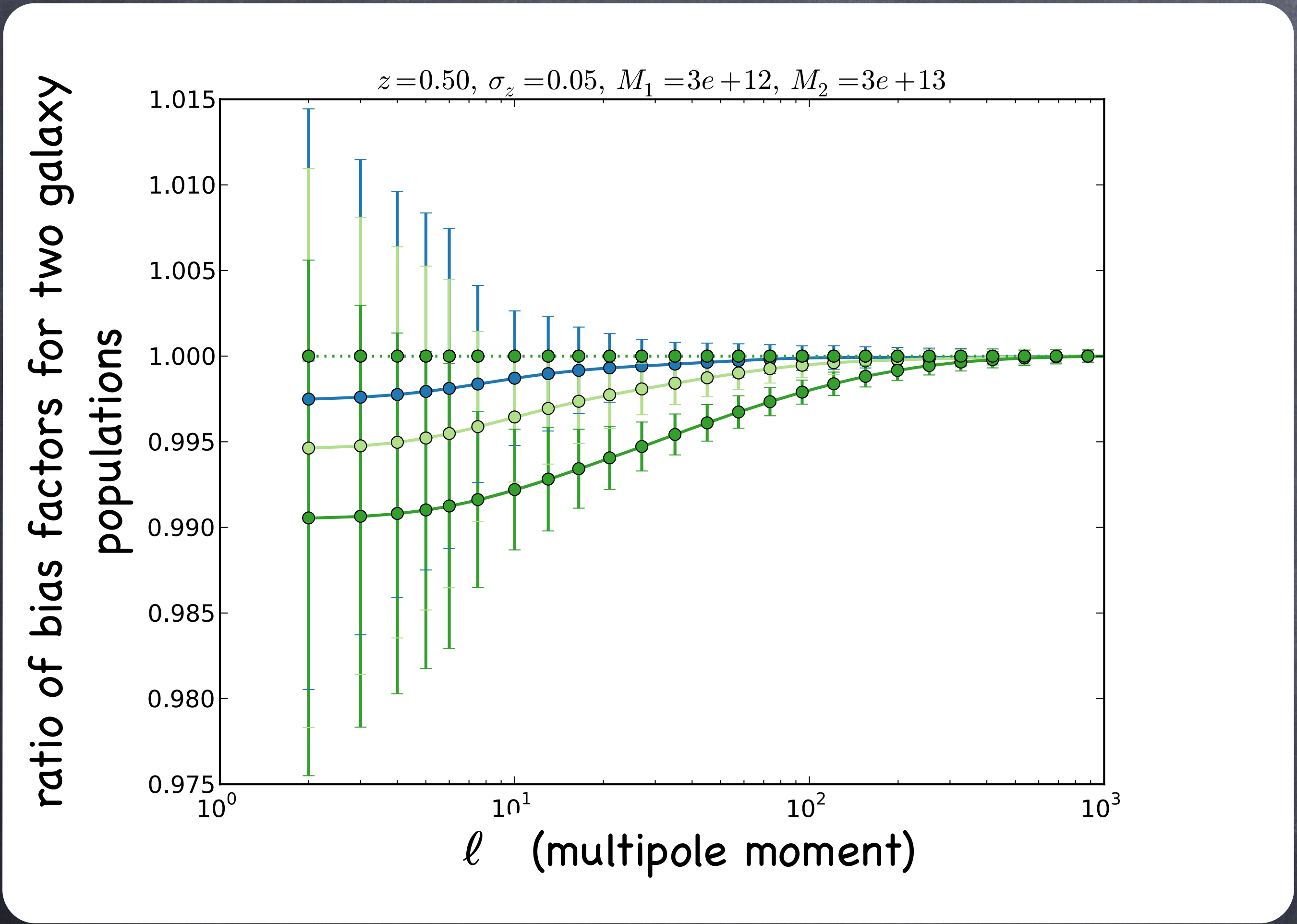
# The scale-dependent halo bias is an observable!




$$\sigma_{b1/b2} \sim \frac{1}{\sqrt{n_1 P_{g2g2}}}$$

(ML in prep.)

# The scale-dependent halo bias is an observable!

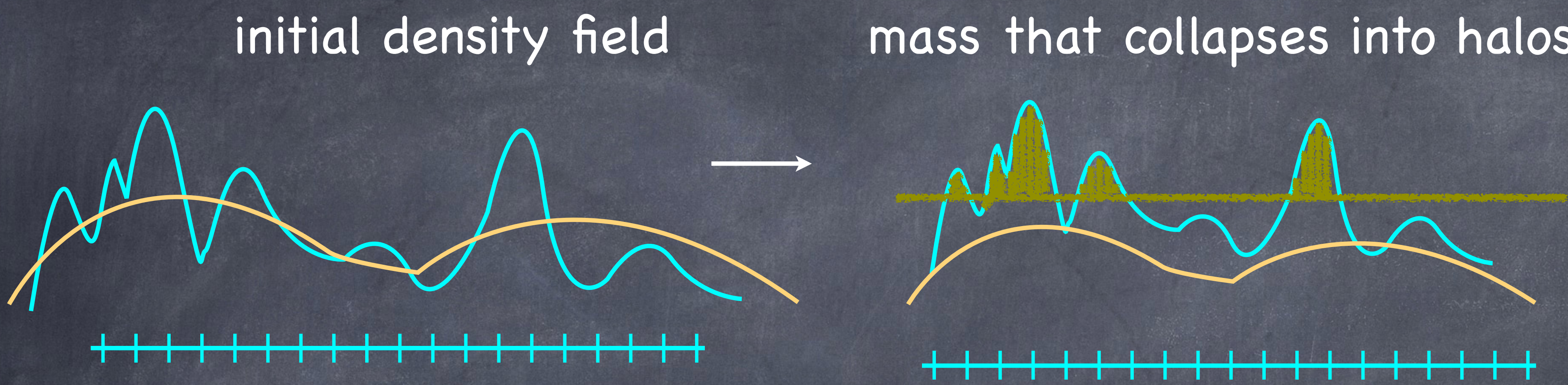



$$\sigma_{b1/b2} \sim \frac{1}{\sqrt{N_\ell\, n_1 C_{g2g2}}}$$

(ML in prep.)

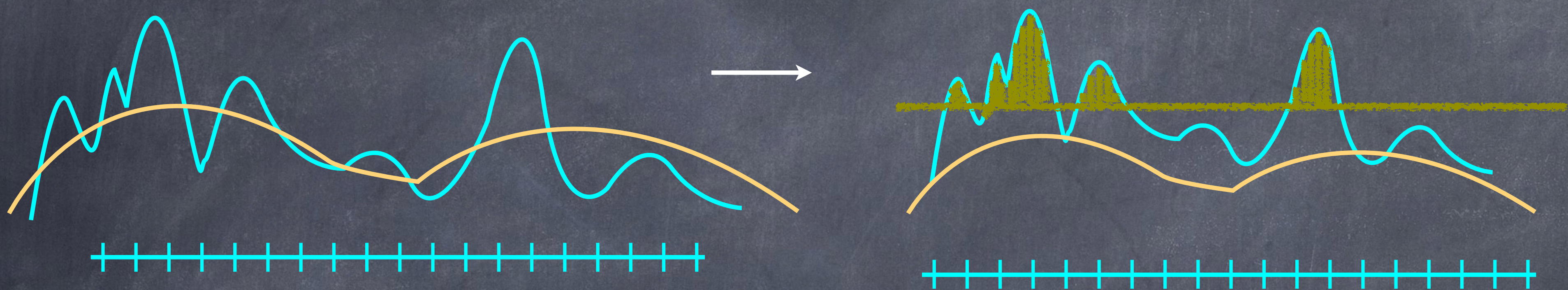
# Fewer massive halos from massive neutrinos

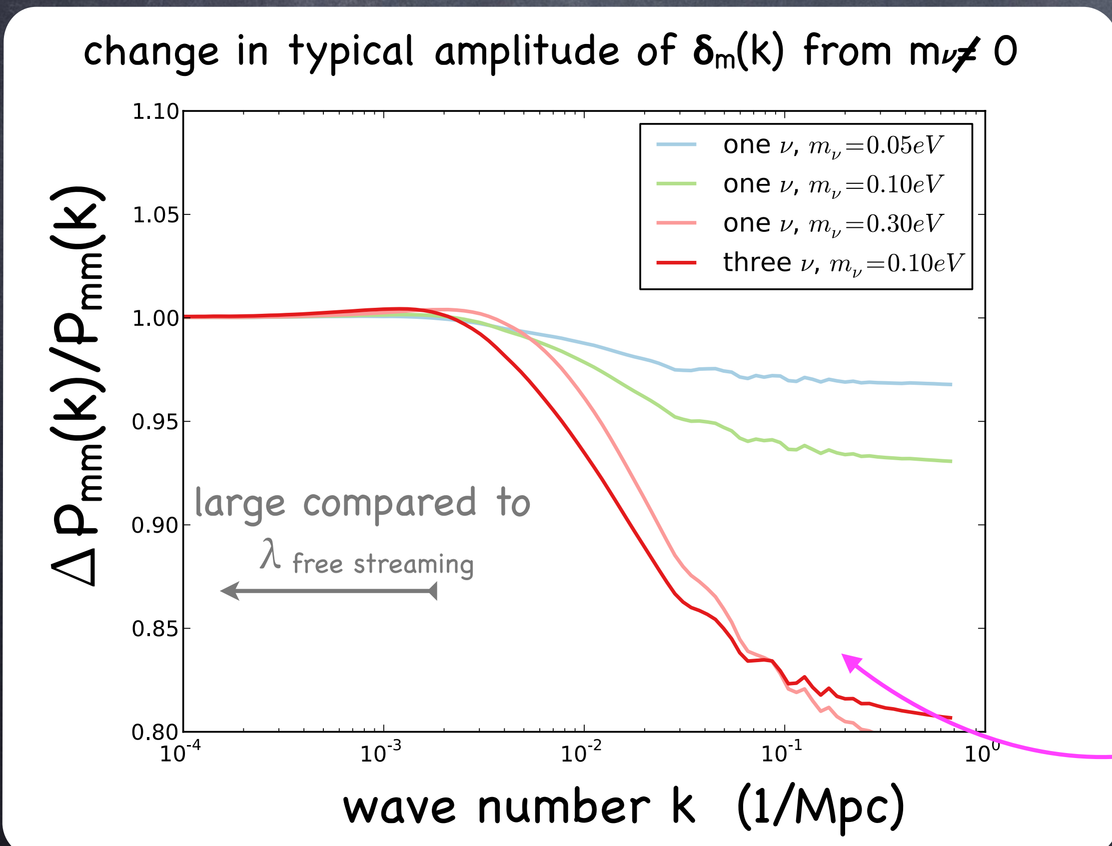
# Fewer massive halos



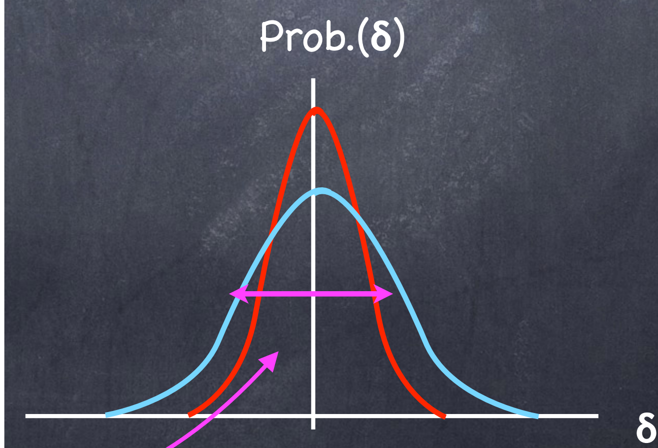
# Fewer massive halos

initial density field | mass that collapses into halos






Fewer large-amplitude density fluctuations



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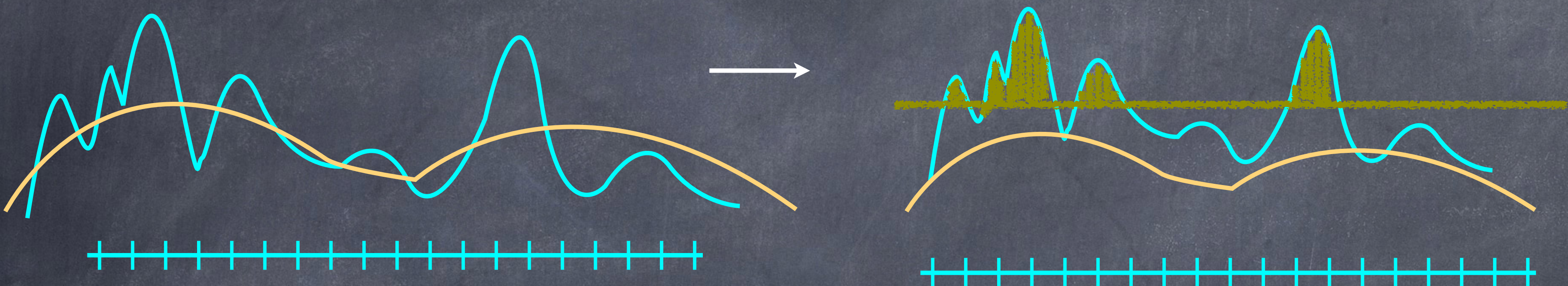
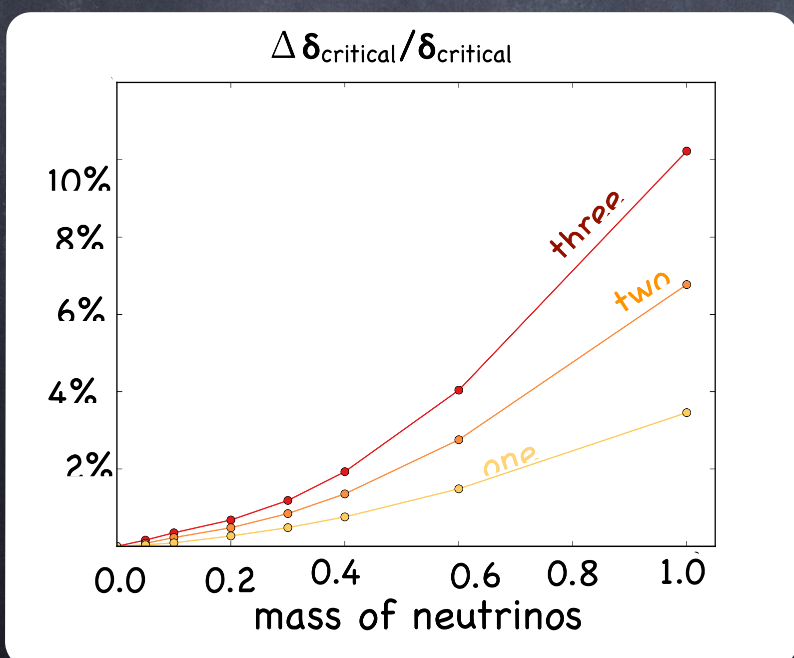
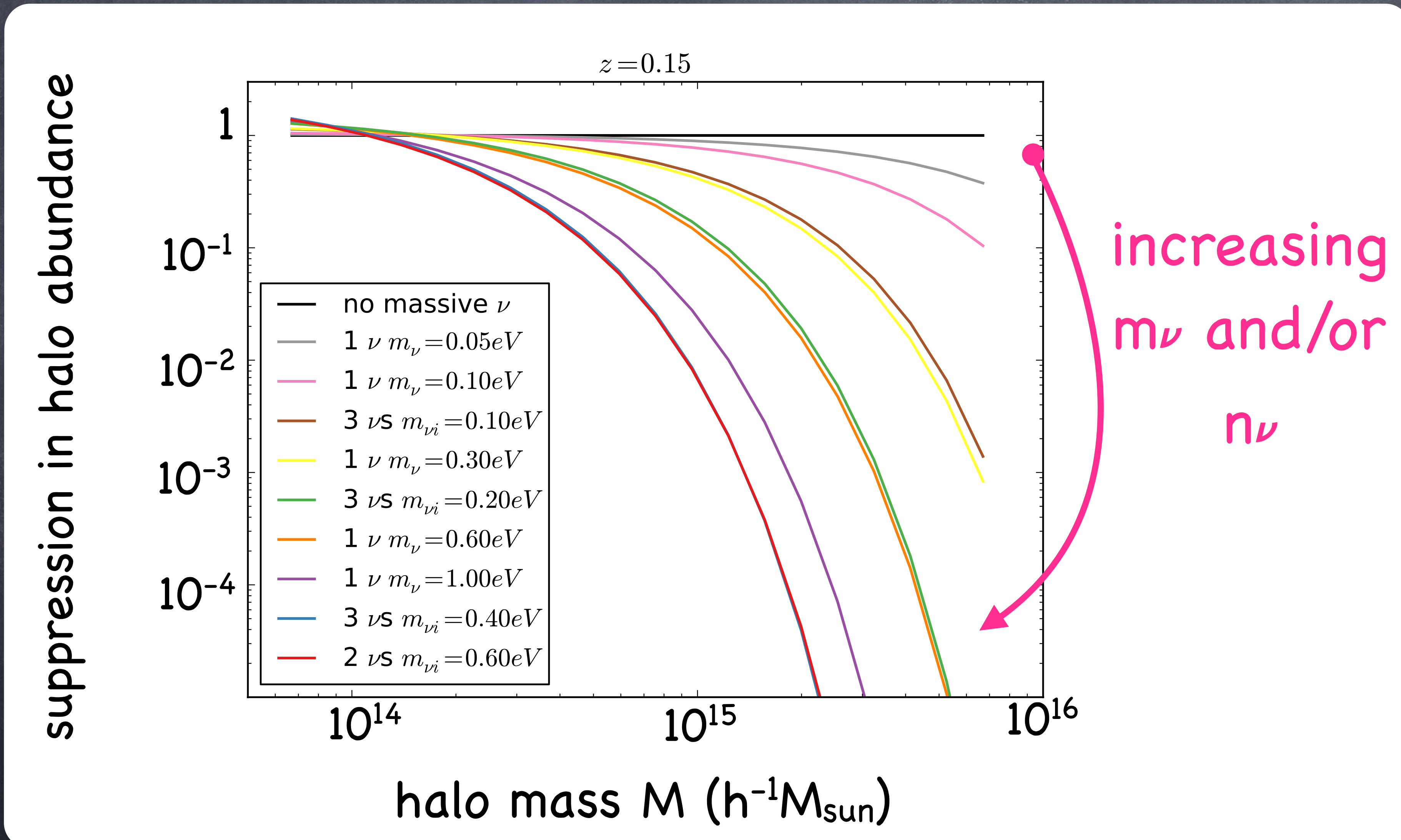





And, higher threshold density to form a halo

# Fewer massive halos

## Many fewer massive halos



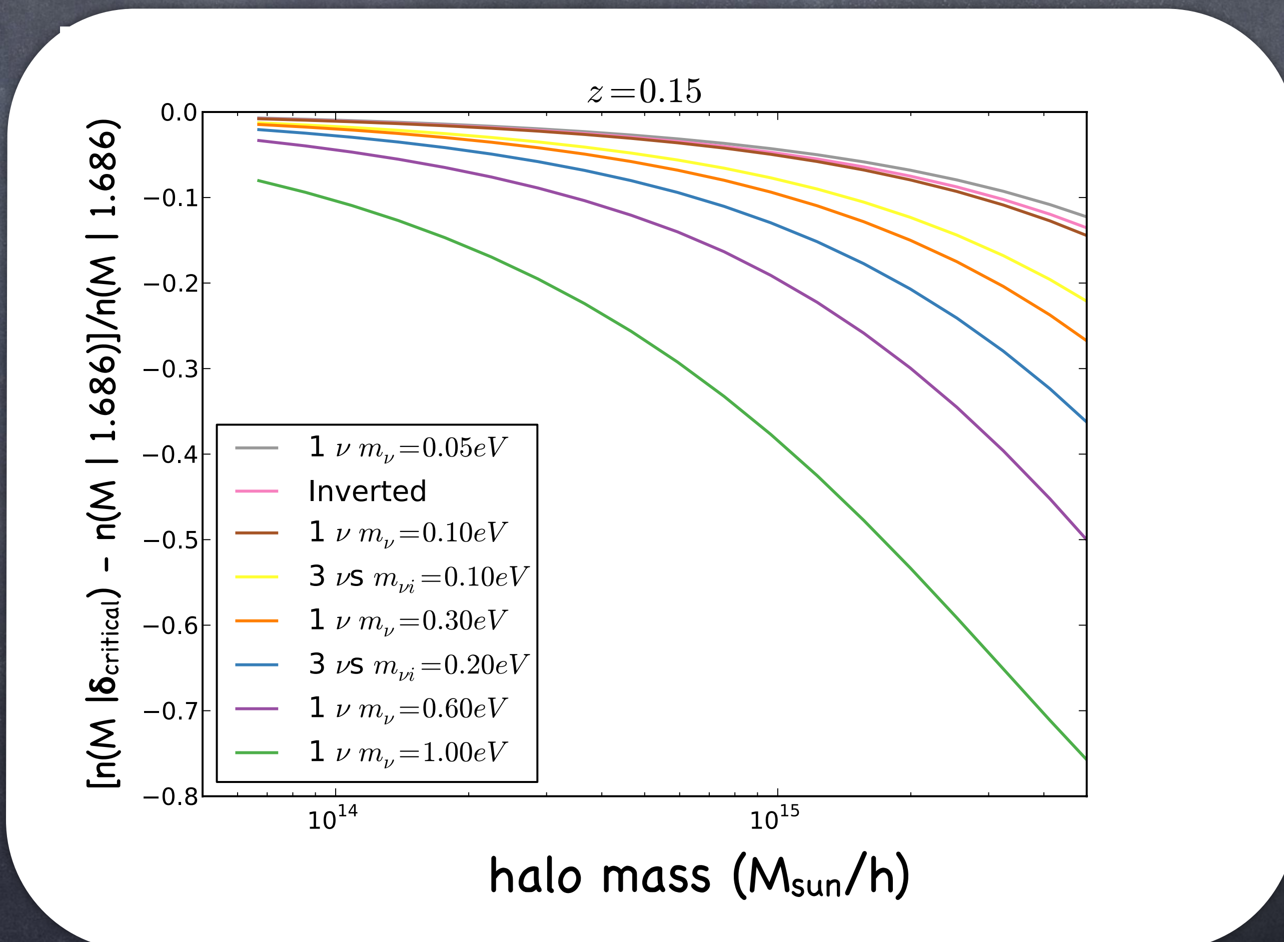

using Bhattacharya et al fitting formula for n(M) with our $\delta_{crit}$

(changes w.r.t. model w same $\Omega_m$ but $\Omega_\nu$ = 0)

Bhattacharya, Heitmann, White, Lukic, Wagner, 2011
ML 2014

# Fewer massive halos

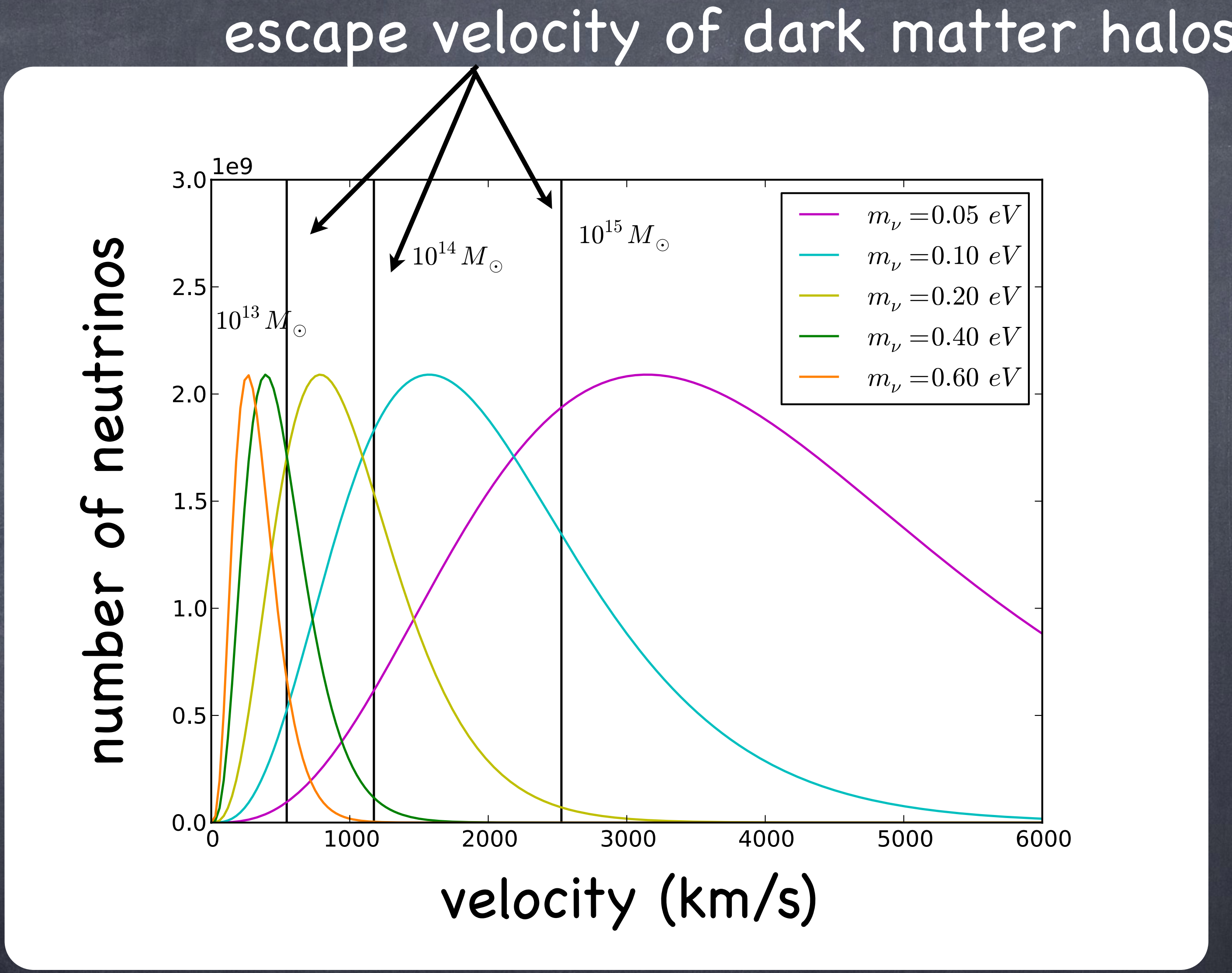
→ Many fewer massive halos




ML 2014

Neutrinos accrete onto these cold dark matter halos

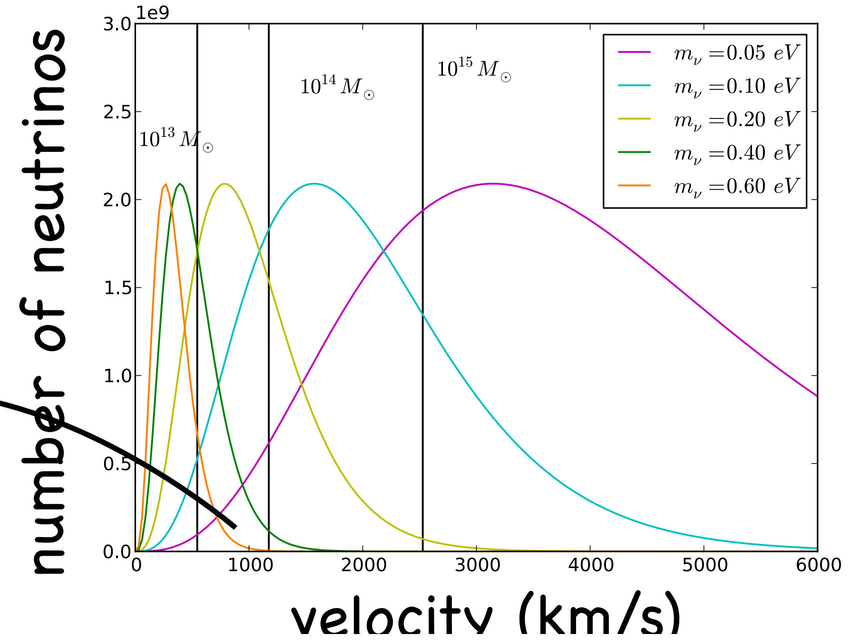
# Neutrino Accretion



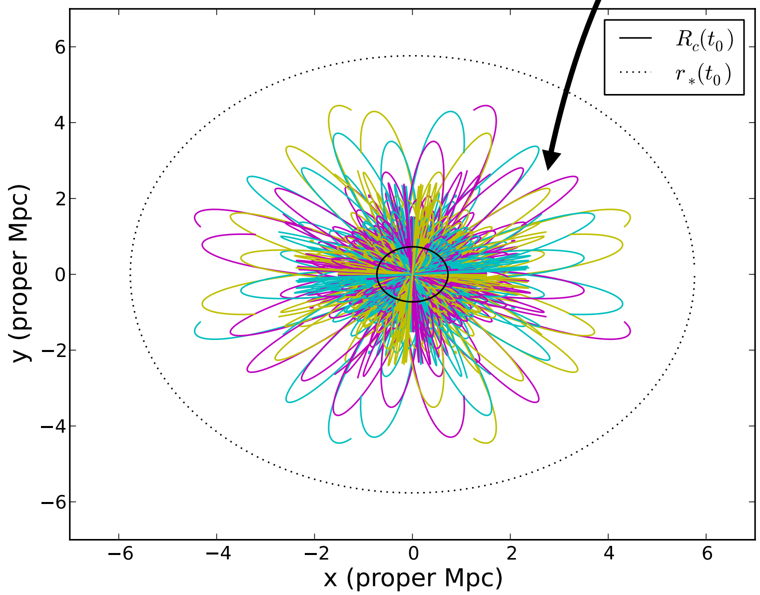

ML & Zaldarriaga 2013

# Neutrino Accretion

low velocity neutrinos end up bound in halos




shown are $m_\nu$ = 0.05eV neutrinos around M = $10^{14}$ $M_{sun}$ halo




see also Ringwald & Wong 2004; Brandbyge, Hannestad, Haugboelle, Wong 2010
Villaescusa-Navarro, Bird, Pena-Garay, Viel 2013

ML & Zaldarriaga 2013

# Neutrino Accretion

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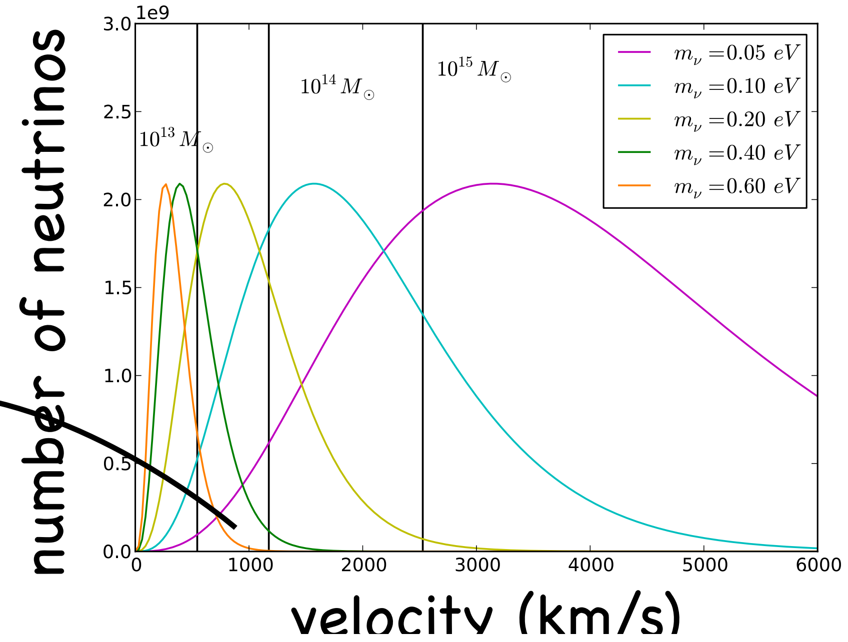


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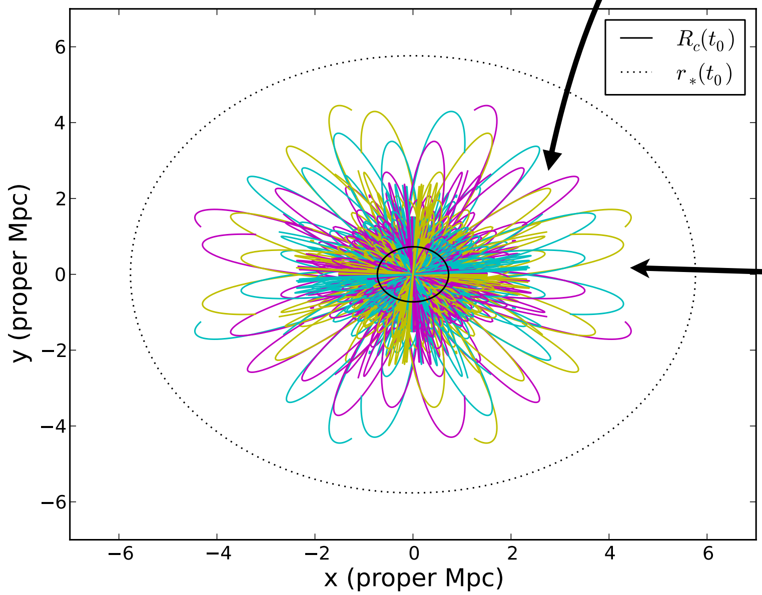
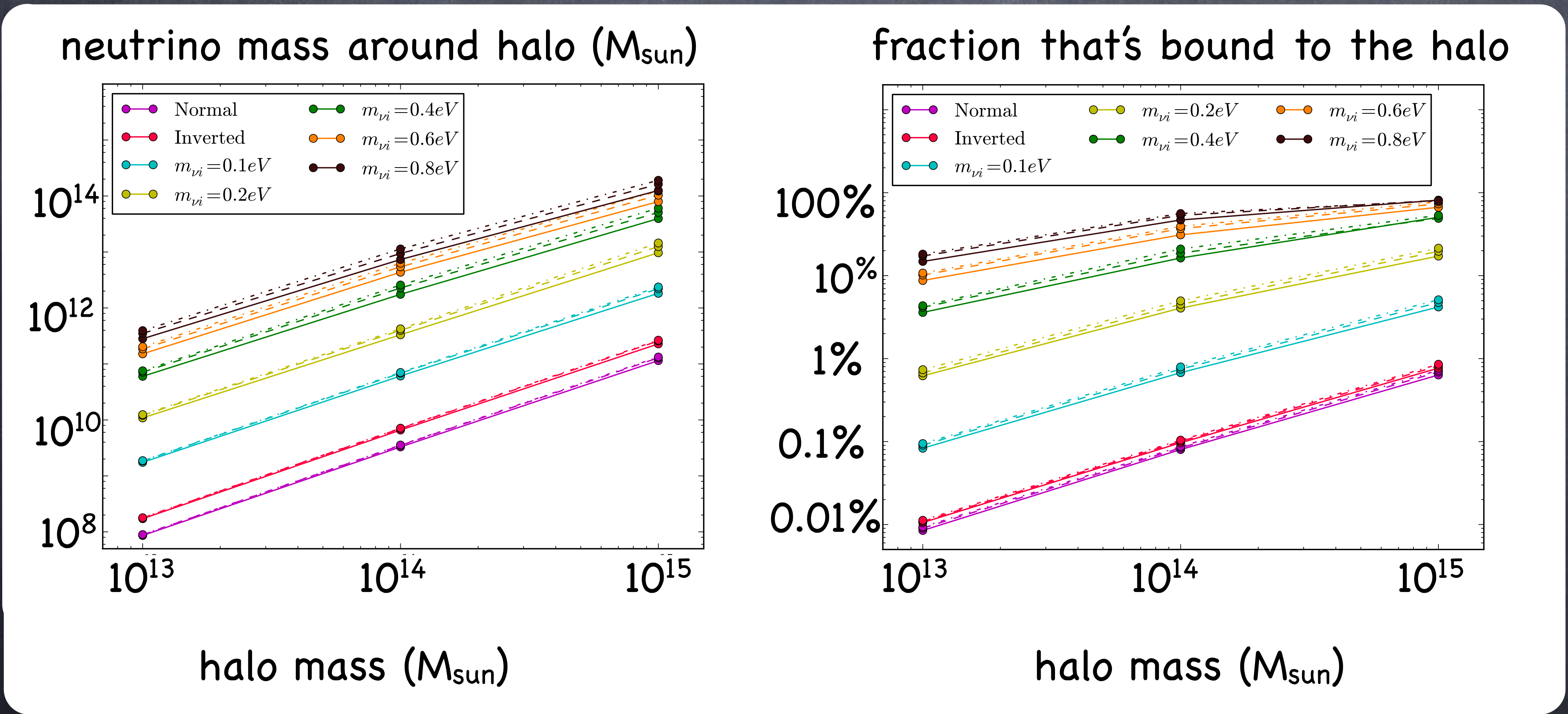



the accreted neutrino halo is puffy in comparison with the CDM!

see also Ringwald & Wong 2004; Brandbyge, Hannestad, Haugboelle, Wong 2010
Villaescusa-Navarro, Bird, Pena-Garay, Viel 2013

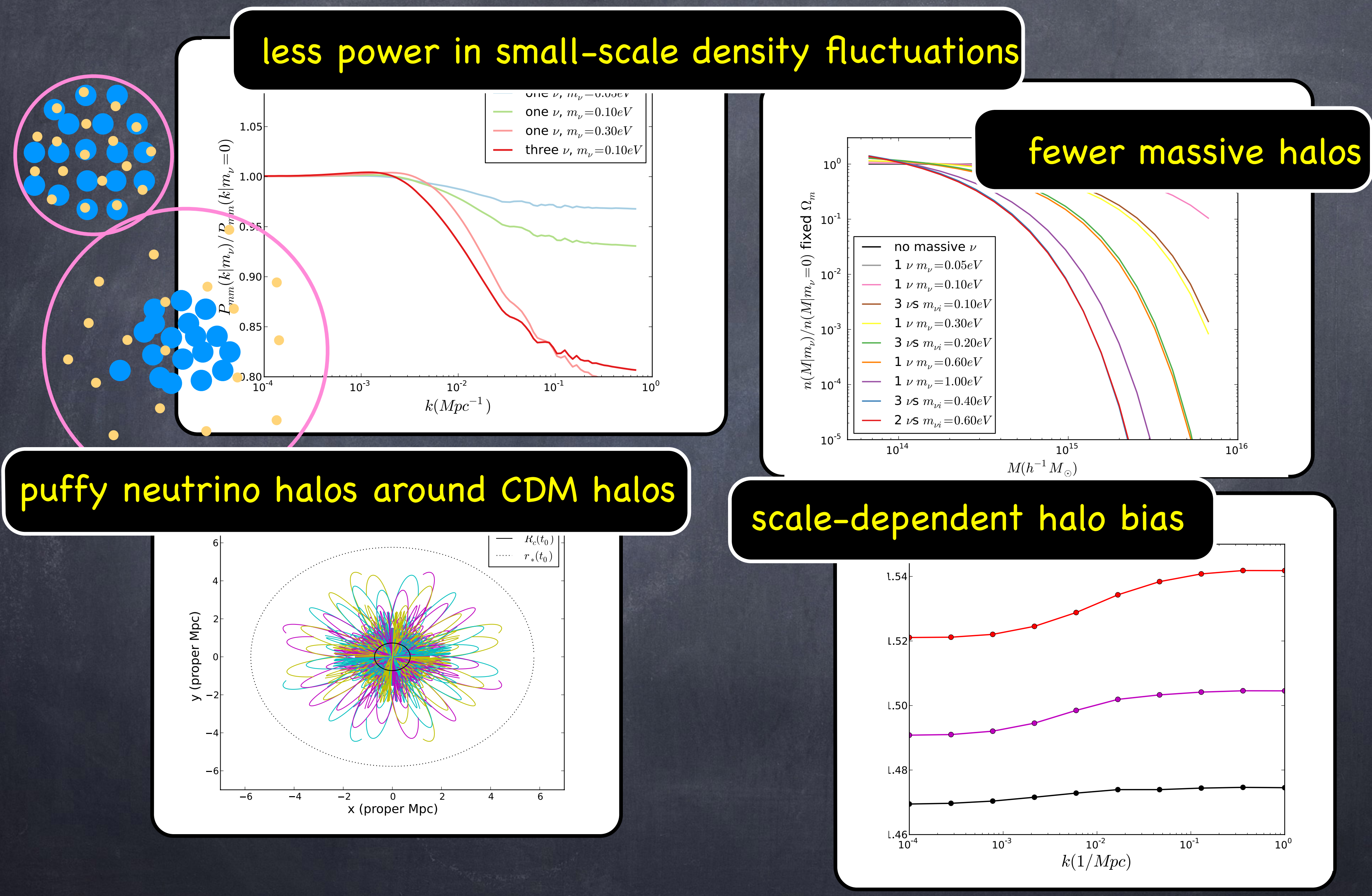
ML & Zaldarriaga 2013

# Neutrino Accretion




ML & Zaldarriaga 2013

# Neutrino Effects in Large-scale Structure



# Accuracy of these predictions?

N-body simulations are the community standard for cold dark matter structure.

Simulations with massive neutrinos?

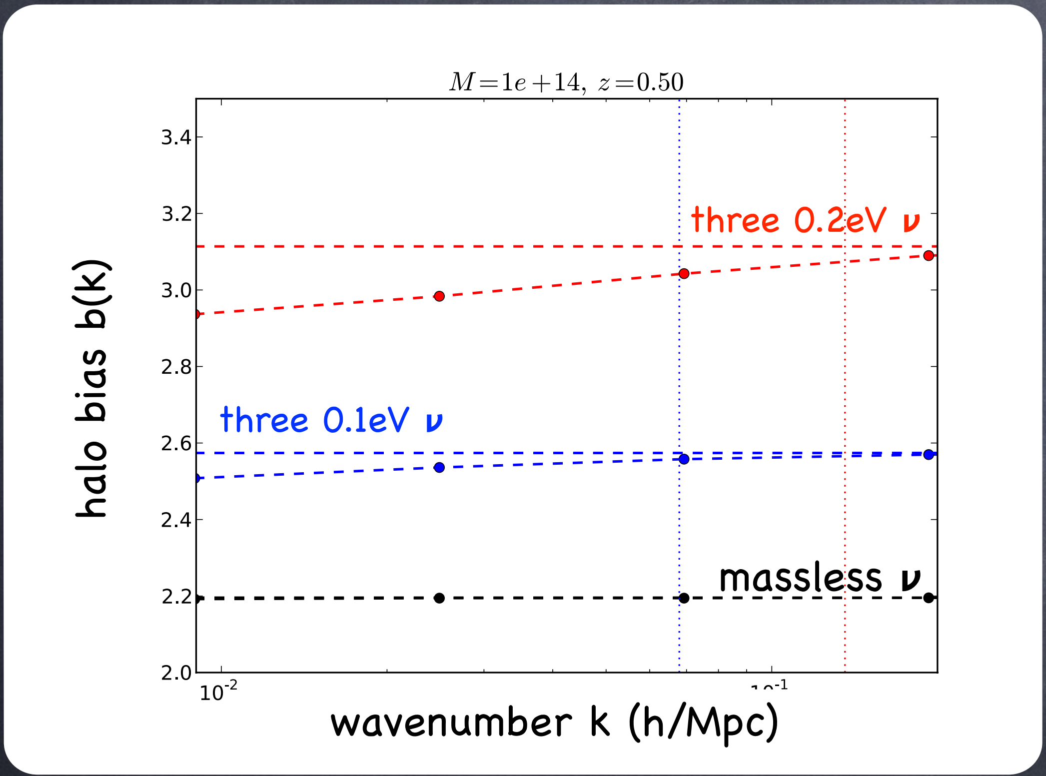
(i) Tricky. very few exist, very new
(ii) Want a model that provides insight into the physical processes responsible for new effects
(iii) Don't want to rerun for every possible neutrino mass hierarchy scenario
(iv) It will be great to make comparisons in the future!

Viel, Haehnelt, Springel 2010; Marulli, Carbone, Viel, Moscardini, Cimatti 2011; Agarwal & Feldman 2011; Brandbyge, Hannestad, Haugboelle, Wong 2012; Upadhye, Biswas, Pope, Heitmann, Habib 2013: Villaescusa-Navarro, Bird, Pena-Garay, Viel 2013;

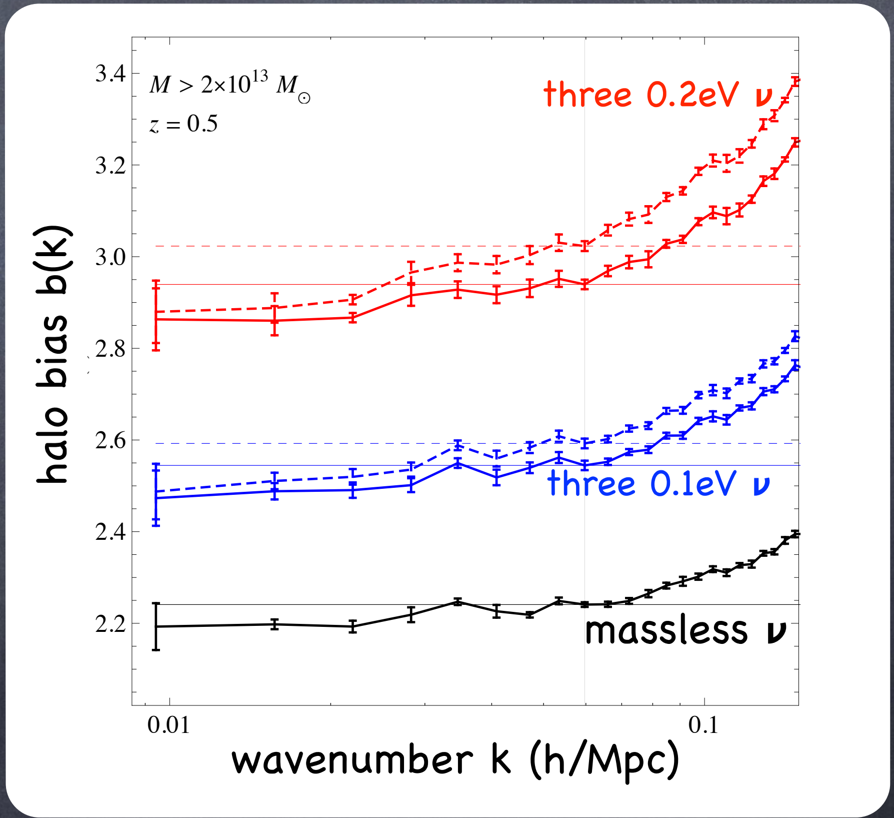
# Scale-dependent bias from massive neutrinos

comparison with sims looks reasonable!

my calculations




simulations from Castorina et al 2013




(ML 2014)

# Conclusions

- Cosmology provides interesting information about neutrinos!
- Scale-dependent halo bias is a new signal of massive neutrinos in large-scale structure
- Scale-dependent halo bias is a new systematic for massive neutrinos in large-scale structure
- Neutrinos decrease abundance of halos — Need to be careful with predictions for $m_\nu \geq 0.3$eV!
- Eventually neutrinos accrete onto very massive halos!